



# Final Report

## Life Cycle Inventory (LCI) of Argonne's Process for Recycling Shredder Residue

Sponsored by  
Argonne National Laboratory  
- Vehicle Recycling Partnership  
- American Plastics Council



**PE EUROPE GMBH**  
Life Cycle Engineering

**Title of the Study:**

**Life Cycle Inventory (LCI) of Argonne's Process for Recycling Shredder Residue**

**Client:**

- **Argonne National Laboratory**
- **Vehicle Recycling Partnership**
- **American Plastics Council**

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## Nomenclature

Abbreviation	Explanation
AP	Acidification Potential
EP	Eutrophication Potential
GWP	Global Warming Potential
POCP	Photochemical Ozone Creation Potential
ODP	Ozone Depletion Potential
PE	Primary energy demand
CO <sub>2</sub>	Carbon dioxide
NO <sub>x</sub>	Nitrogen oxide
SO <sub>2</sub>	Sulfur dioxide
VOC	Volatile organic Compounds
VRP	Vehicle Recycling Partnership
ARGONNE	Argonne National Laboratory
LCI	Life Cycle Inventory
EoL	End of Life
CWT	Changing World Technology
SR	Shredder residue
ABS	Acrylonitrile-butadiene-styrene
PPO	Polyphenylene oxide
PC	Polycarbonate
HIPS	High Impact Polystyrene
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
PU	Polyurethane
PET	Polyethylene terephthalate



## 1 Introduction

The Vehicle Recycling Partnership (VRP) has set an internal goal to develop a life cycle model to evaluate and analyze all promising technologies that can recycle end of life vehicles, which supports the understanding of environmental benefits offered by new technologies. The EoL model is set-up modularly to be able to “plug in” new technologies.

Therefore, the VRP is analyzing a variety of technologies for analyzing end of life vehicles considering technical, economical, and environmental aspects.

The first LCI module of the EoL model was based on the Salyp shredder residue separation process (VRP PO# 722) and the second LCI module represents the process flow of Changing World Technology’s (CWT) thermal conversion process (TCP).

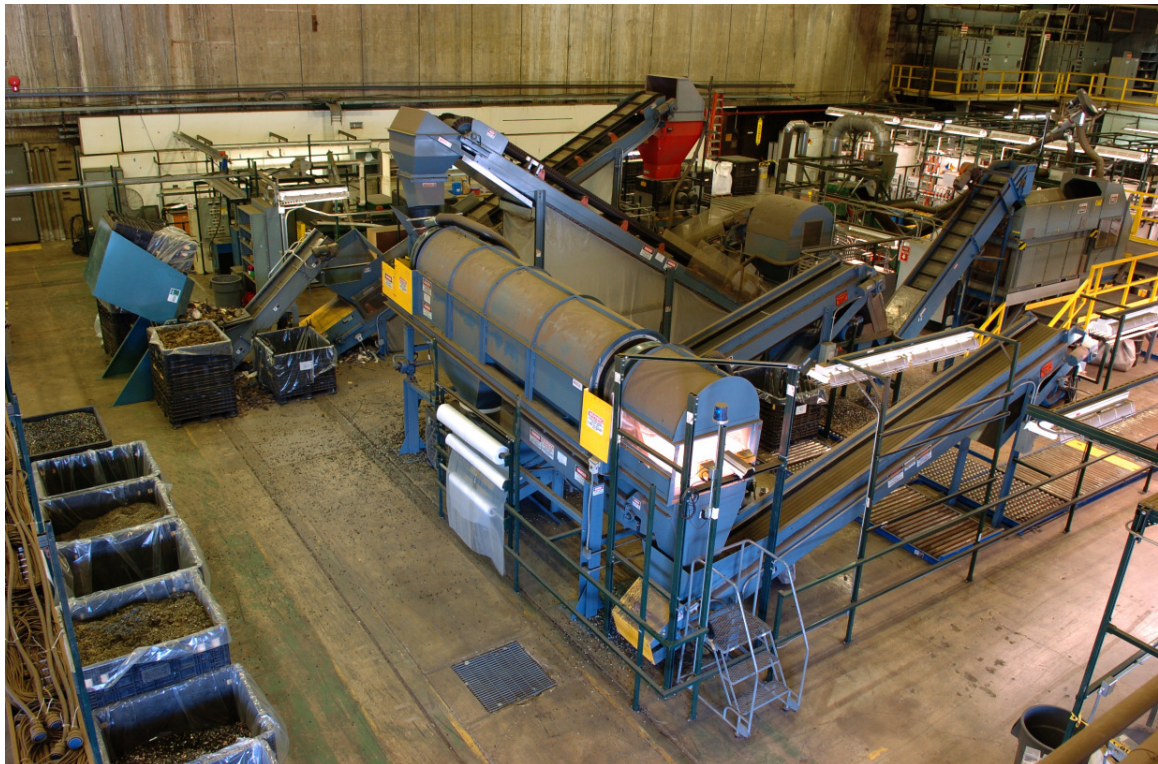
This LCI study has been conducted to create a further module, representing the Argonne shredder residue recycling process. This module contributes to achieving a better understanding of the environmental impacts/ benefits of the Argonne process and can be used to model different scenarios of shredder residue separation and adjust it to different boundary conditions.

The LCI model has been created based on the information provided by Argonne National Laboratory (ARGONNE) and assumptions and estimations made by the project team.

## 2 Introduction of the Argonne process

The Argonne process separates shredder residue material into different valuable products using power, water, salt and surfactant. The Argonne process consists of two main steps:

1. Mechanical Separation Plant Figure 2-1: The mechanical separation plant consists of an oversized separation station, shredder for size reduction, a two-stage rotary drum, magnets for ferrous metal separation, an eddy current separation system (recovery of non-ferrous metals) and granulators for size reduction of plastics required for separation of individual plastics from each other by the Froth Flotation plant.
2. Froth Flotation Separation Plant Figure 2-2: The Froth Flotation plant consists of conveyors for feeding the plastics into the separation tank, several froth-flotation/density-separation tanks and tanks for recovering the separated plastics fractions



**Figure 2-1:** A picture of Argonne's Mechanical Separation Pilot Plant



**Figure 2-2: A picture of Argonne's Froth Flotation pilot plant**

Besides the emissions related to the generation of electricity and the production of the auxiliary materials, no specific process emissions to atmosphere occur from the different process steps.





### 3 Goal and Scope of the study

#### 3.1 Goal of the study

The goal of this study was to gain knowledge on the environmental effects associated with Argonne's shredder residue recycling process including the handling of the produced fractions.

To meet the above stated goal, a flexible and process specific LCI model of the Argonne process was created, which enables the project partners to model different scenarios of ASR handling and adjust it to different boundary conditions.

This can be accomplished by the incorporation of relevant parameters. The adjustable boundary conditions include:

- Composition of SR input
- Energy needed
- Auxiliary materials needed (Salt, Water, Surfactant)

For all listed boundary conditions, parameters have been defined within the LCI software model. Therefore, the model offers maximum flexibility for scenario analysis, which is the basis for a detailed understanding of the ARGONNE process.

#### 3.2 Scope of the study

The scope of the project was the creation of a parameterized LCI model of the ARGONNE process, which enables the VRP to gain knowledge on the environmental effects/ benefits of the ARGONNE process within different boundary conditions.

##### **Product System**

The study has considered all process steps of the ARGONNE process. All relevant input and output flows are modeled. The functional unit has been defined at the kick off meeting by the project team. The model covers Argonne's Mechanical Separation Plant and the Froth Flotation Plant (see Figure 3-1 and Figure 3-2).

##### **System Boundaries**

The system boundaries of the LCI models include all relevant material and process flows as shown within Figure 3-1 and Figure 3-2. Information on all relevant processes includes material and energy flows. LCI profiles of the needed materials and energies are taken from the GaBi 4 database. The figures and tables in this chapter depict the material flow sheet of 10,000 lb of shredder residue but the plant is designed to handle 40,000 lb per hour.



### Material Flow Sheet of the Argonne Mechanical Separation Plant Based on 10,000 lb of Shredder Residue

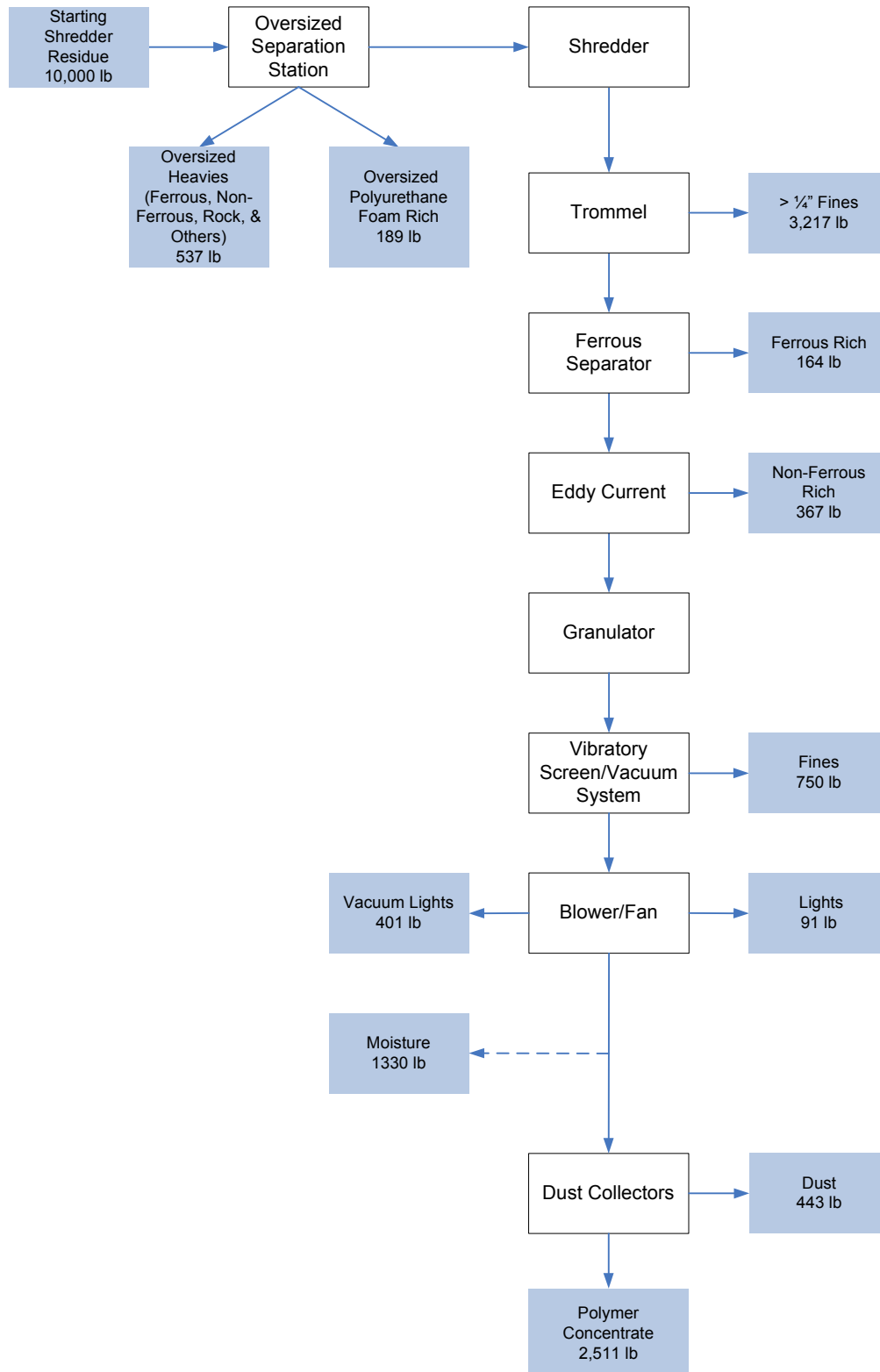
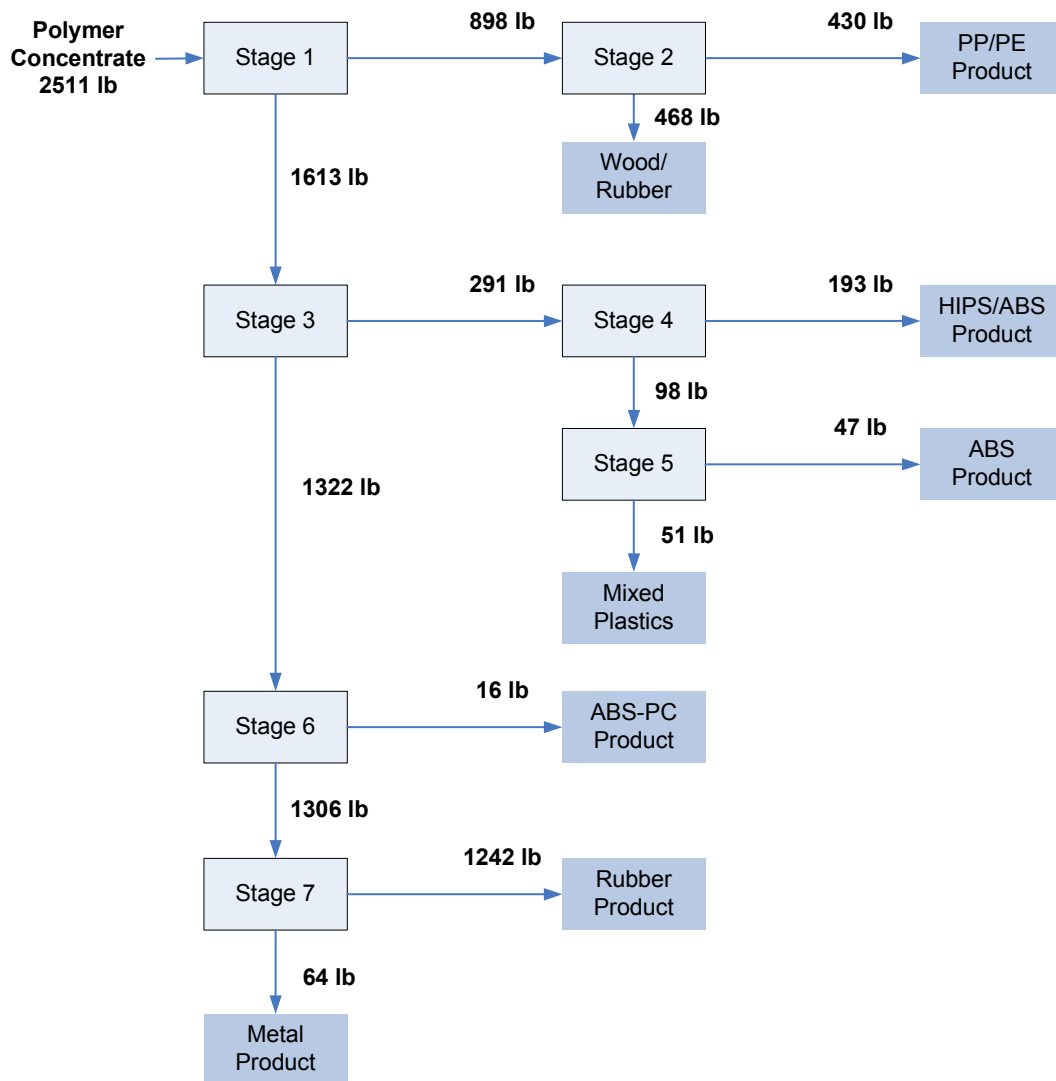


Figure 3-1: System boundaries of the Mechanical Separation Plant



### Material Flow Sheet of the Argonne Plastic Separation Plant Based on 10,000 lb of Shredder Residue



**Figure 3-2: System boundaries of the Froth Flotation Plant**

One important strength of the LCI model is that the composition of the SR input can be changed. The analyses discussed within this report are based on the compositions shown in Table 3-1 for the mechanical separation plant and in Table 3-2 for the Froth Flotation plant.





**Table 3-1: Composition of each fraction recovered from the mechanical separation plant – basis for analyses (based on 10,000 lb shredder residue input)**

Fraction	Starting Shredder Residue	Starting Shredder Residue										Polymer Concentrate
		Oversized Heavies	Oversized Polyurethane Foam Rich	1/4" Fines	Ferrous Rich	Non-Ferrous Rich	Vacuum Lights	Fines	Lights	Moisture	Dust	
Polypropylene	289	0	0	0	4	9	19	0	13	0	0	244
Polypropylene (Filled)	33	0	0	0	0	0	0	0	2	0	0	31
ABS	154	0	0	0	1	2	3	0	0	0	0	148
Polyethylene	245	0	0	0	2	4	15	0	6	0	0	218
Polystyrene	63	0	0	0	1	2	3	0	1	0	0	56
Nylon	73	0	0	0	1	2	4	0	1	0	0	65
Polyvinyl Chloride	132	0	0	0	0	0	0	0	0	0	0	132
PPO	16	0	0	0	0	0	1	0	0	0	0	15
PC/ABS	7	0	0	0	0	0	0	0	0	0	0	7
Polycarbonate	123	0	0	0	0	0	3	0	0	0	0	120
Trace Plastics	38	0	0	0	0	0	1	0	0	0	0	37
Unidentified Plastics	51	0	0	0	0	0	3	0	0	0	0	48
Rubber and Rigid Polyurethane	1324	6	0	0	2	49	14	0	3	0	0	1250
Wood	52	0	0	0	0	0	0	0	0	0	0	52
Metals	723	279	0	0	148	239	0	0	0	0	0	57
Non-Plastics, Foams, and Fibers	5347	252	189	3217	5	60	335	750	65	0	443	31
Moisture	1330	0	0	0	0	0	0	0	0	1330	0	0
Total	10000	537	189	3217	164	367	401	750	91	1330	443	2511

\*All units are in pounds



**Table 3-2: Composition of each fraction covered from the Froth Flotation plant – basis for analyses (based on 10,000 lb of shredder residue input)**

Fraction	Starting Shredder Residue	Polymer Concentrate	Polymer Concentrate							
			PP/PE Product	Wood Rubber	HIPS/ABS Product	ABS Product	Mixed Plastics	ABS-PC Product	Metal Product	Rubber Product
Polypropylene	289	244	213	31	0	0	0	0	0	0
Polypropylene (Filled)	33	31	0	7	10	5	0	0	0	9
ABS	154	148	0	6	83	35	12	1	0	11
Polyethylene	245	218	195	20	3	0	0	0	0	0
Polystyrene	63	56	0	6	42	0	0	0	0	8
Nylon	73	65	0	5	1	2	3	0	1	53
Polyvinyl Chloride	132	132	0	0	0	0	0	1	1	130
PPO	16	15	0	0	13	1	1	0	0	0
PC/ABS	7	7	0	0	0	1	0	5	0	1
Polycarbonate	123	120	0	0	0	0	0	8	1	111
Trace Plastics	38	37	0	0	2	1	2	0	0	32
Unidentified Plastics	51	48	0	1	0	0	1	0	0	46
Rubber and Rigid Polyurethane	1324	1250	19	332	24	2	31	1	5	836
Wood	52	52	0	33	15	0	1	0	0	3
Metals	723	57	0	0	0	0	0	0	56	1
Non-Plastics, Foams, and Fibers	5347	31	3	27	0	0	0	0	0	1
Moisture	1330									
Total	10000	2511	430	468	193	47	51	16	64	1242

\*All units are in pounds.

The project team is aware of the fact that the assumed shredder residue compositions shown here represent an average composition for shredder residues produced by five different shredders. The data presented in this report is exemplary and it has been agreed that the discussion/ analysis of the model/ results within the final report should be based on these compositions.



## 4 Information Sources

### 4.1 Data collection

Data within the LCI model originates from different sources.

The creation of the LCI model is based on primary data collection at the ARGONNE facility, assumptions made by the project team and LCI profiles of the GaBi 4 database.

#### Process flows

The mass flow is related to the composition of the SR input. The amount of salt, surfactant and water needed depends on the amount of shredder input material.

#### Energy and Auxiliaries

The production of energies, intermediates products, material profiles and the handling of the produced fractions required for modeling were taken from the GaBi 4 database. The power grid mix is based on US boundary conditions. The surfactant material is modeled specific for this project on base of provided information by ARGONNE. The LCI profiles for salt and water are taken from the GaBi 4 database.

#### Assumptions

In the present study the following assumptions have been made by the project team:

- Auxiliary material salt is mineral salt
- Auxiliary material surfactant is an alkoxyated linear alcohol
- Amount of auxiliary materials is depending on the mass throughput of the polymer concentrate
- Electric motors of each piece of equipment are operating at full energy 16h a day (for processing 40,000 lb per hour of shredder residue)
- Share of materials in the fraction 'Rubber and rigid Polyurethane' is 75% Rubber and 25% Rigid Polyurethane
- Allocation for the elements in the organics fraction:
  - al → aluminium
  - cu → copper
  - mg → ferrous
  - mn → ferrous
  - ti → ferrous
  - si → glass and sand
  - na → glass
  - ca → rocks



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**Transportation**

Transportation is not included.

**Credit for recovered products**

The credits for the recovered materials, gained out of the mechanical separation process and the Froth Flotation process, are modeled as shown in Table 4-1 and Table 4-2. The benefits are calculated on the basis of “inverted” processes<sup>1</sup>.

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<sup>1</sup> Inverted inventories represent the avoided environmental impacts which would occur if the materials, energies etc. would have been produced/ generated according to the commonly used process. For example the benefits assigned to the steam generated by the incineration process are calculated based on the avoided steam production using natural gas.



**Table 4-1: Credits for recovered products and fractions out of the Mechanical Separation Plant<sup>2</sup>**

Fraction		Handling / Substitution
<i>Oversized Heavies</i>		
Containing of	Rubber and Rigid Polyurethane	Waste for landfill
	Metals	Metals products
	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Oversized Polyurethane Foam Rich</i>		
Containing of	Non-Plastics, Foams, Fibers	10% waste for landfill 90% product recovery
<i>1/4" Fines</i>		
Containing of	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Ferrous Rich</i>		
Containing of	Polypropylene	Waste for landfill
	ABS	Waste for landfill
	Polyethylene	Waste for landfill
	Polystyrene	Waste for landfill
	Nylon	Waste for landfill
	Rubber and Rigid Polyurethane	Waste for landfill
	Metals	90% product recovery
	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Non-Ferrous Rich</i>		
Containing of	Polypropylene	Waste for landfill
	ABS	Waste for landfill
	Polyethylene	Waste for landfill
	Polystyrene	Waste for landfill
	Nylon	Waste for landfill
	Rubber and Rigid Polyurethane	Waste for landfill
	Metals	65% product recovery
	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Vacuum Lights</i>		
Containing of	Polypropylene	Energy recovery
	ABS	Energy recovery
	Polyethylene	Energy recovery

<sup>2</sup> For detailed information on the material fraction of the Mechanical Separation Plant see Appendix A 1



	Polystyrene	Energy recovery
	PPO	Energy recovery
	Nylon	Energy recovery
	Polycarbonate	Energy recovery
	Trace Plastic	Energy recovery
	Unidentified Plastics	Energy recovery
	Rubber and Rigid Polyurethane	Energy recovery
	Non-Plastics, Foams, Fibers	Energy recovery
<i>Fines</i>		
Containing of	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Lights</i>		
Containing of	Polypropylene	Energy recovery
	Polypropylene (filled)	Energy recovery
	Polyethylene	Energy recovery
	Polystyrene	Energy recovery
	Nylon	Energy recovery
	Rubber and Rigid Foam	Energy recovery
	Non-Plastics, Foams, Fibers	Energy recovery
<i>Dust</i>		
Containing of	Non-Plastics, Foams, Fibers	Waste for landfill
<i>Moisture</i>		Evaporating during processing



**Table 4-2: Credits for recovered products and fractions out of the Froth Flotation Plant<sup>3</sup>**

Fraction	Handling / Substitution
PP/PE product	Product recovery (100% PP)
Wood product	Energy recovery (100%)
HIPS/ABS product	Product recovery (100% low PS)
ABS product	Product recovery (100% ABS)
Mixed plastics product	Energy recovery (100%)
ABS/PC alloy product	Product recovery (100% ABS/PC)
Metal product	Product recovery (25% steel / 22.5% aluminium / 52.5% copper)
Rubber product	Product recovery (100% EPDM)

Material recycling: the product considered will be credited with the environmental burdens associated with the material the recovered fraction is substituting. The default setting value for the substitution factor<sup>4</sup> is given with 10%. This factor is parameterized and can be changed for each material fraction individually.

Energy recovery: recovered plastic fraction with a possibility of energy recovery will be modeled as energy recovery.

Landfill: fractions considered for landfill are modeled as waste for landfill (in the present no GaBi 4 dataset is used)

## 4.2 Creation of the model

The flexible parameterized model has been created within the software system GaBi 4 based on the material and energy flows provided by Argonne. It has been agreed by the project team that the share of the recovered material fraction of the absolute quantitative mass contribution to the shredder input are independent of the total SR composition. For example 84.4 % of the polypropylene (PP) share of the SR composition ends up in the polymer concentrate independent of the total mass of PP.

<sup>3</sup> For detailed information on the material fraction of the Plastic Separation Plant see Supplement A 2

<sup>4</sup> The substitution factor in percent represents the rate of recovered material which is substituted.





#### 4.2.1 ARGONNE Mechanical Separation Plant

Based on the information provided by ARGONNE the model for the Mechanical Separation Plant is built up. The energy demand for the equipment per process step is given as well as the fraction output per process step based on 10,000 lb shredder input. The mass of the shredder input is a flexible parameter. Also the time of usage for the single equipments is a flexible parameter. The default setting of the operating time is given with 1 hour. The default settings for the energy consumption of the equipment are displayed in Table 4-3. The default settings presented in Table 4-3 are based on full capacity operation (40,000 lb shredder residue per hour).

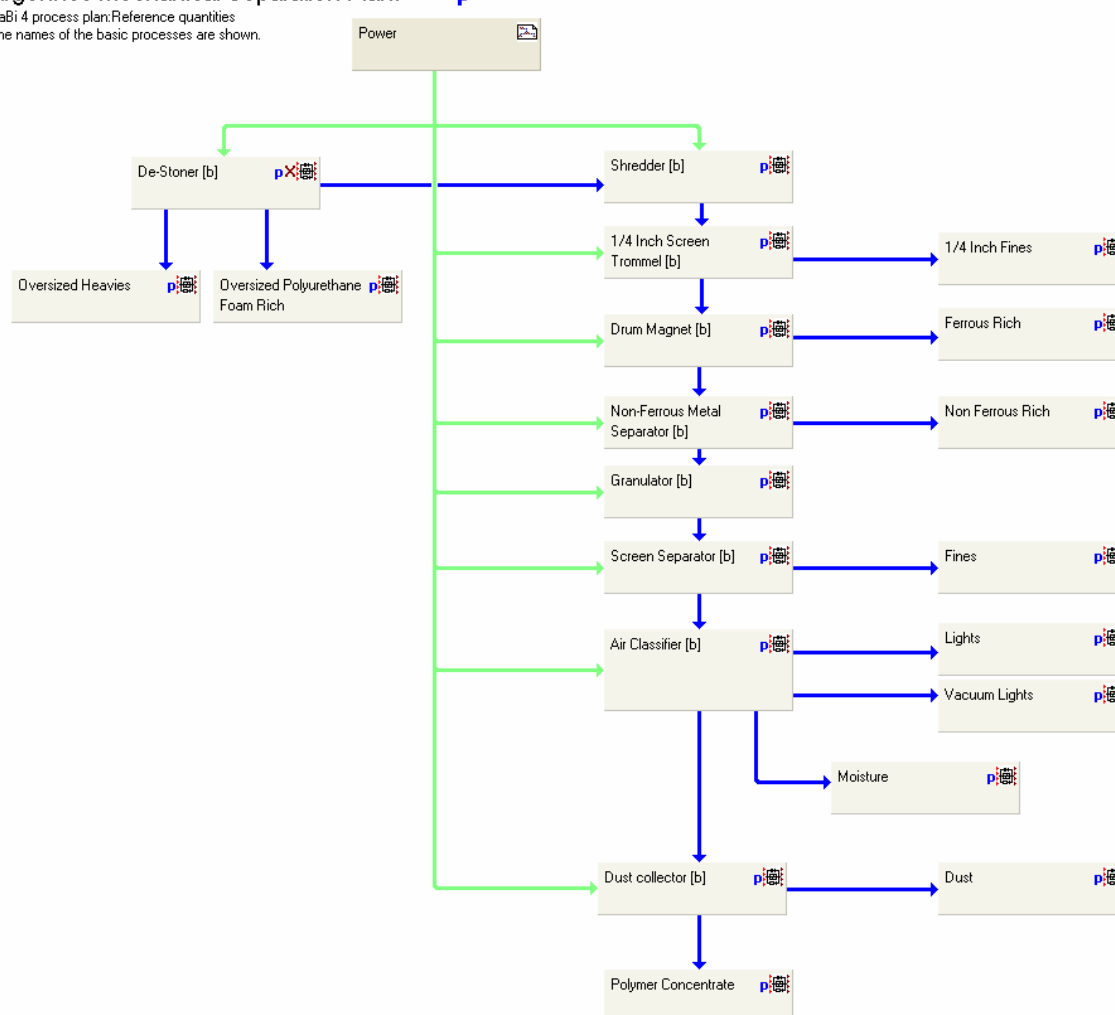
**Table 4-3: Energy default settings for the process steps – Mechanical Separation Plant**

Process step	Energy Input
Oversized Separation Station	25 hp (18.7 kW)
Shredder	350 hp (261 kW)
Trommel	15 hp (11.2 kW)
Ferrous Separator	5 hp (3.7 kW)
Eddy Current	13 hp (9.7 kW)
Granulator	400 hp (298 kW)
Vibratory Screen / Vacuum System	20 hp (14.9 kW)
Blower / Fan	3 hp (2.2 kW)
Dust Collector	5 hp (3.7 kW)

Figure 4-1 illustrates the LCA model of the Mechanical Separation Plant.

#### Argonnes Mechanical Separation Plant

GaBi 4 process plan: Reference quantities  
The names of the basic processes are shown.



**Figure 4-1: LCA Model Mechanical Separation Plant**

For updating the present model or to run different scenarios there are various options possible. In general it is possible to change the default settings or to change the fix values. The following parameters can be adjusted to changing boundary conditions:

- Shredder composition
- Shredder Input (full capacity operation: 40,000 lb/hr)
- Energy consumption of the equipment
- Operating time of the used equipment
- Credits for the recovered material fractions
- efficiencies of processes handling the recovered material fractions



Within Table 4-4 the scenario for handling the produced fractions of the Mechanical Separation Plant are shown as agreed by the project team.

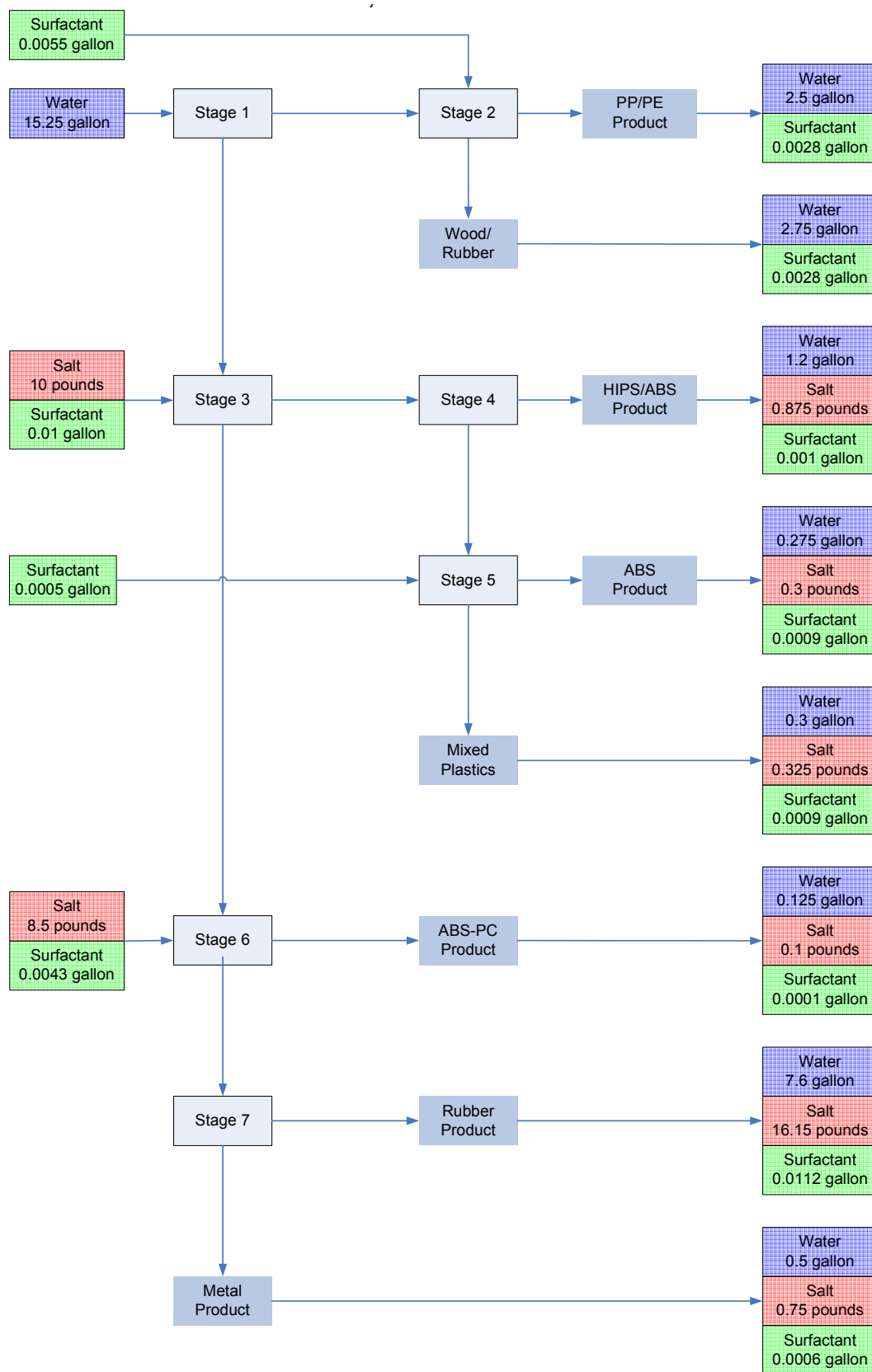
**Table 4-4: Scenarios for handling products from the ARGONNE process (Mechanical Separation plant)**

Fraction / Product	Handling / Substitution
Oversized Heavies	52% Metals (50% steel / 50% aluminium) 48% Rock (waste for landfill)
Oversized Polyurethane Foam Rich	10% PET fiber / 90% PU
1/4" Fines	Waste for landfill
Ferrous Rich	90% Ferrous metals (steel) 10% Residual materials (waste for landfill)
Non-Ferrous Rich	65% Nonferrous metals (83% aluminium, 13% copper, 4 % brass) 35% Residual materials (waste for landfill)
Vacuum Lights	Waste for energy recovery
Fines	Waste for landfill
Lights	Waste for energy recovery
Dust	Waste for landfill

#### 4.2.2 ARGONNE Froth Flotation Plant

The model for ARGONNE Froth Flotation Plant is based on provided information by Argonne. The energy demand for the equipment per process step is given as well as the consumption of the auxiliary materials salt, surfactant and water and the fraction output per process step based on 10,044 lb polymer concentrate input. The mass of the polymer concentrate input of the Froth Flotation plant is a calculated output of the Mechanical Separation Plant. The amount of the auxiliary materials salt, surfactant and water is related to the polymer concentrate input. The default settings for the usage of salt, surfactant and water are illustrated in Figure 4-2. The amount of needed auxiliary materials is automatically calculated.

Figure 4-2 shows exemplarily the material flow sheet of the froth flotation process based on 10,000 lb shredder residue which means 2,511 lb polymer concentrate.



**Figure 4-2:** Auxiliary material flow sheet – Froth Flotation Plant (per 10,000 lb shredder input → 2,511 lb polymer concentrate)



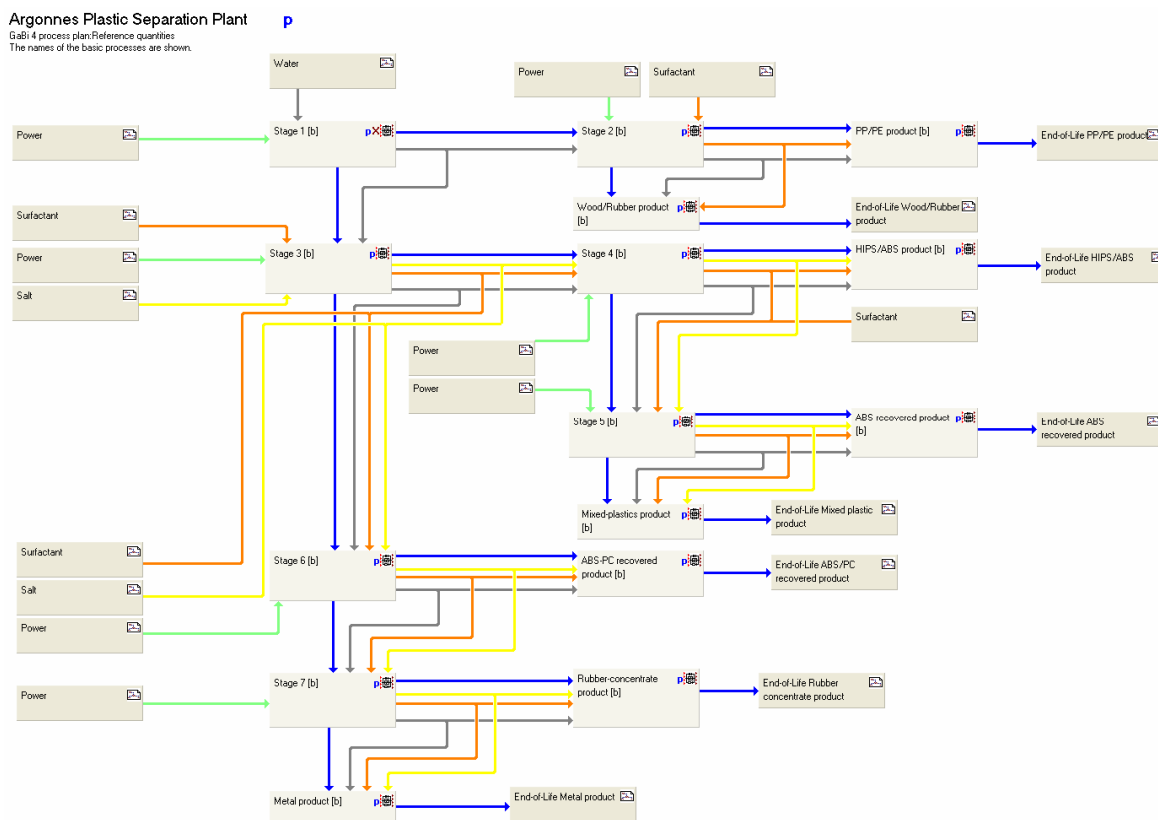
Also the time of usage for the single equipments is modeled as a flexible parameter. The default setting of the operating time is given with 1 hour. The default settings for the energy consumption of the equipment are displayed in Table 4-5. The default settings presented in Table 4-5 are based on 10,044 lb polymer concentrate.

**Table 4-5: Energy default settings for the process steps –Froth Flotation Plant**

Process step	Energy Input
Stage 1	1.5 hp (1.1 kW)
Stage 2	1.5 hp (1.1 kW)
Stage 3	1.5 hp (1.1 kW)
Stage 4	1.5 hp (1.1 kW)
Stage 5	1.5 hp (1.1 kW)
Stage 6	1.5 hp (1.1 kW)
Stage 7	1.5 hp (1.1 kW)

The energy and the auxiliary consumption of the Froth Flotation plant are depending on the input of the polymer concentrate. The recovered fractions of the single process steps vary only by the amount of polymer concentrate.

Figure 4-3 illustrates the LCA model of Froth Flotation plant.



**Figure 4-3: LCA Model Froth Flotation Plant**

For updating the present model or to run different scenarios there are various options possible. In general it is possible to change the default settings or to change the fix values. The following parameters can be adjusted to changing the boundary conditions:

- Energy consumption of the equipment
- Operating time of the used equipment
- Credits for the recovered material fractions
- Loss factor<sup>5</sup> for each of the recovered material fractions

<sup>5</sup> The substitution factor in percent represents the rate of recovered material which is substituted.



Within Table 4-6 the scenario for handling the produced fractions of the Froth Flotation Plant are shown as agreed by the project team.

**Table 4-6: Scenarios for handling products from the Argonne Froth Flotation process**

<b>Fraction / Product</b>	<b>Substituted material</b>	<b>Mass of substituted material [lb]</b>
PP/PE	PP	1,716
Wood/Rubber	Energy Recovery	1,872
HIPS/ABS	Low grade PS	776
ABS	ABS	188
Mixed Plastics	Energy Recovery	204
ABS/PC	ABS 50% / PC 50%	64
Metal	25% steel / 52.5% copper / 22.5% aluminium	256
Rubber	EPDM	4,968

Within the scenarios, the produced fractions are handled in different ways. The fractions are either handled by landfill or energy recovery or product recovery. The product recovery of the rubber fraction shows nearly in all categories the highest amount of credits. This is due to the fact that mass amount of rubber in the polymer concentrate is high (4,968 lb).

The results for the described scenario are given in the following parts of the report.





## 5 Results of the analysis of the Argonne process

A flexible parameterized LCI model of the Argonne process has been created. It provides the user with an efficient way to evaluate the process, while considering additional life cycle stages with further usage of the produced fractions.

The results are discussed for the overall process and also individually for the mechanical process and the froth flotation process. As the Froth Flotation plant is discussed in detail, the polymer concentrate has not been considered when discussing the mechanical part.

### 5.1 LCI model of Argonne process

As the material composition of SR varies in different regions, the LCI model has been created in a parameterized way to be easily adjustable to varying material compositions. The defining parameters are tracked through the complete model and the auxiliary materials/energies needed for running the process are related to the SR input.

LCI data sets of each separated fraction can be created on the basis of the GaBi model.

In the following the results of the agreed scenario, is displayed for primary energy (PE) demand, Global Warming Potential (GWP100), Acidification potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP) and CO<sub>2</sub> emissions. The impact assessment, as explained in Appendix B, is based on the life cycle inventory. Assessments can be created easily for either other impact categories or specific emissions using the created LCI model.

The following figures show selected results based on the shredder residue composition shown in Table 5-1.



**Table 5-1: Material composition of the starting shredder residue (based on 40,000 lb of shredder residue)**

Fraction	Mass of Starting Shredder Residue in lb
Polypropylene	1,260
Polypropylene (filled)	144
ABS	680
Polyethylene	1,076
Polystyrene	276
Nylon	320
Polyvinylchloride	584
PPO	72
PC/ABS	32
Polycarbonate	544
Trace Plastic	168
Unidentified Plastic	224
Rubber	4,380
Rigid Polyurethane	1,460
Flexible Polyurethane	3,132
Wood	232
Copper	344
Brass	40
Ferrous (steel, metals in the fines are included)	5,552
Aluminium	1,708
Rocks	1,792
Fibers (PET, PP and cotton) <sup>6</sup>	6,080
Glass	1,392
Thermoset plastics	1,088
Moisture	7,420
<b>Total</b>	<b>40,000</b>

## 5.2 Primary energy demand

In the following the primary energy demand for the Mechanical Separation Plant and the Froth Flotation Plant is given. Both process steps show a benefit regarding primary energy

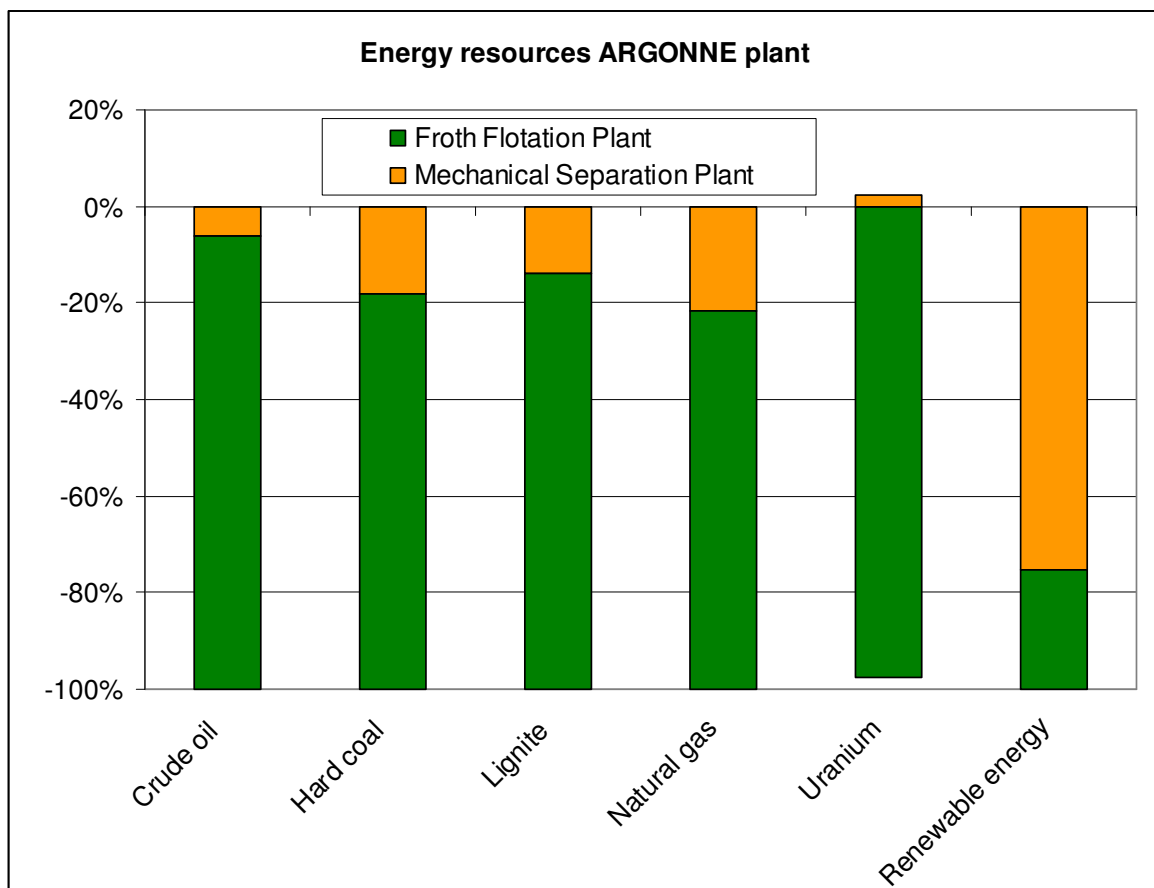
<sup>6</sup> the Fibers contain mainly PET fibers but also can contain other fibers, for the purpose of this study it is assumed that the fraction is 100% PET fibers



demand. The benefit related to the Froth Flotation plant is higher. This is mainly due to the fact that the separated fractions have the potential to replace polymer material.

**Table 5-2: Primary energy demand in MJ for the Argonne plant (based on 40,000 lb shredder residue)**

	Total	Mechanical Separation Plant	Froth Flotation Plant
Crude oil [MJ]	-181936	-11041	-170896
Hard coal [MJ]	-12158	-2193	-9966
Lignite [MJ]	-7900	-1106	-6794
Natural gas [MJ]	-141074	-30786	-110288
Uranium [MJ]	-12259	298	-12556
Renewable energy [MJ]	-4757	-3578	-1179



**Figure 5-1: Primary energy demand (renewable and non renewable energy)**

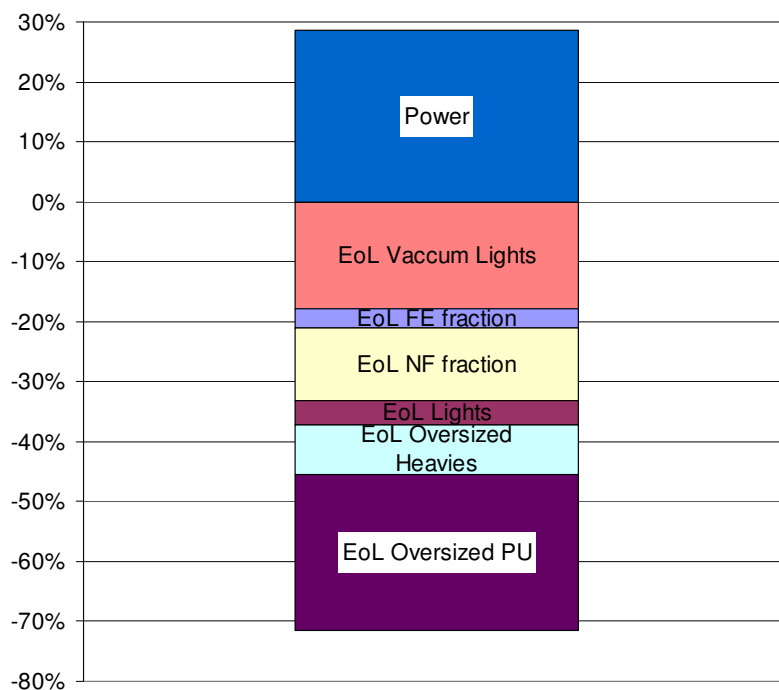


### **Mechanical Separation Plant**

The primary energy demand based on the used power for running the mechanical separation plant is offset by the credits related to the material substitution/ energy recovery of the separated fraction. The power consumption is dominated by the installed shredder and the granulator. Combined they consume approximately 90% of the needed power.

Even though the mass of the PU foam share of the “Oversized PU foam rich fraction” is relatively low compared to the “Vacuum Lights” (“Vacuum Lights” more than double that of PU, see also Table 3-1 and Table 4-4), PU from the Oversized PU foam rich fraction contributes the highest overall credit as it is being substituted for the material with the highest primary energy demand and the PU from the Vacuum Lights is handled by energy recovery.

For detailed information on the absolute values, please see Appendix B 1.



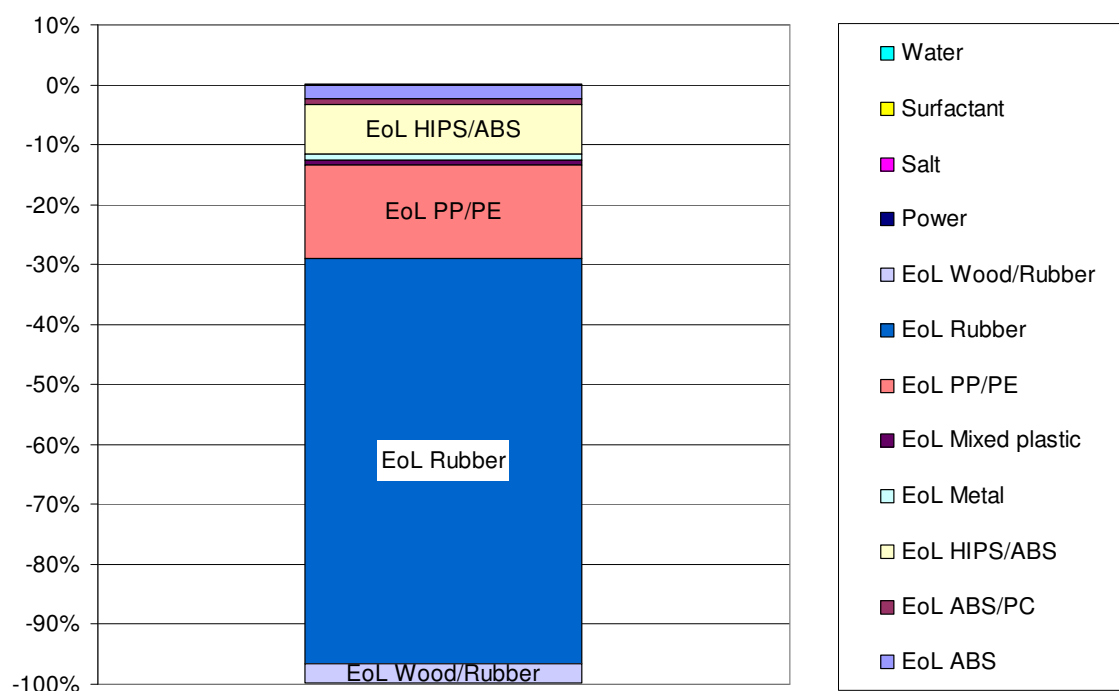
**Figure 5-2: Detailed primary energy demand Mechanical Separation Plant.**

### **Froth Flotation Plant**

As the main consumers of energy are located in the mechanical part of the process, the primary energy demand of the Froth Flotation Plant is not significant. Also the contribution of the auxiliary materials is low compared to the credits associated with the recovered fractions. All separated fractions of the Froth Flotation Plant contribute credits to the overall primary energy demand. The biggest shares of credit are due to the recovery of the rubber concentrate product, followed by the recovery of the PP/PE product and third fraction is the recovery of the HIPS/ABS product. This effect is mainly related to the quantity of each fraction substituting different polymer fractions.

The primary energy demand related to the power and auxiliary materials needed for running the Froth Flotation Plant is negligible compared to the other quantities. Therefore the values do not show up Figure 5-3.

For detailed information on the absolute values see Appendix B 2.



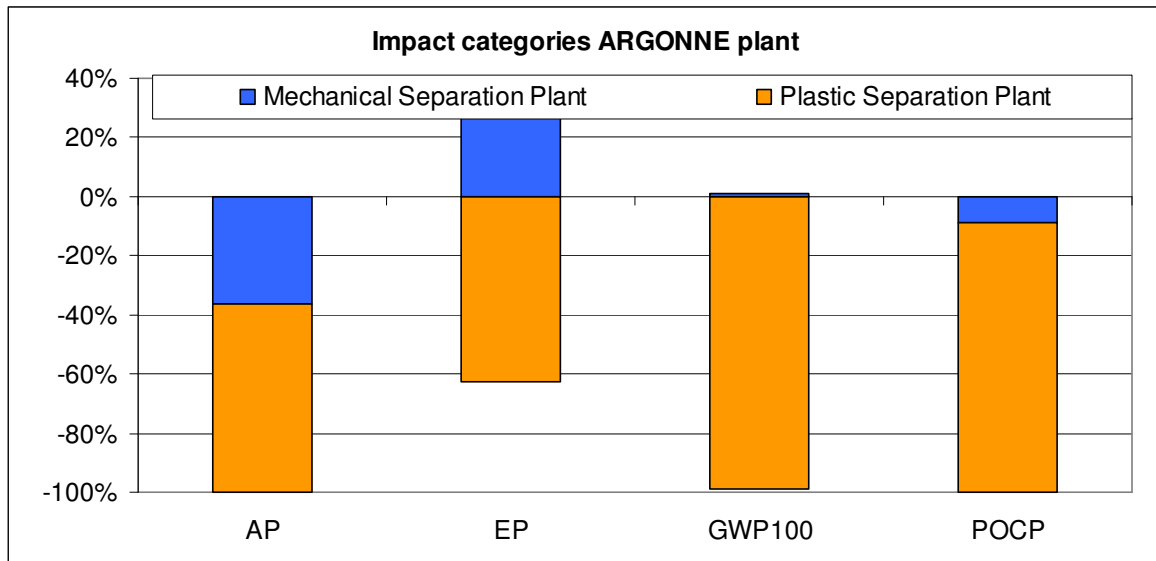
**Figure 5-3: Detailed primary energy demand Froth Flotation Plant**

### 5.3 Selected impact categories

Considering the complete ARGONNE plant the usage of the Argonne processes gives benefits for all impact categories. Even as the 'Mechanical separation' causes burdens regarding the impact categories EP, GWP100 and ODP the credits associated with the Froth Flotation is higher for all impact categories and therefore the overall plant shows benefits for all analyzed impact categories, see Table 5-3 and Figure 5-4.

**Table 5-3: Selected impact categories for the Argonne plant**

	Total	Mechanical Separation Plant	Froth Flotation Plant
AP [kg SO <sub>2</sub> -Equiv.]	-36,15	-13,18	-22,97
EP [kg Phosphate-Equiv.]	-0,46	0,66	-1,12
GWP100 [kg CO <sub>2</sub> -Equiv.]	-8554	72,34	-8627
POCP [kg Ethene-Equiv.]	-17,84	-1,57	-16,27



**Figure 5-4: Impact categories (Argonne plant)**

In the next two Figures the ARGONNE plant is analyzed for each process step. Figure 5-5 displays the benefits and burdens of the Mechanical Separation Plant and Figure 5-6 shows the benefits and burdens of the Froth Flotation Plant.

The positive percentage values show the burdens of the considered impact category specified by the single fractions. The negative percentage values give the gained benefit for each impact category specified by the single fractions.

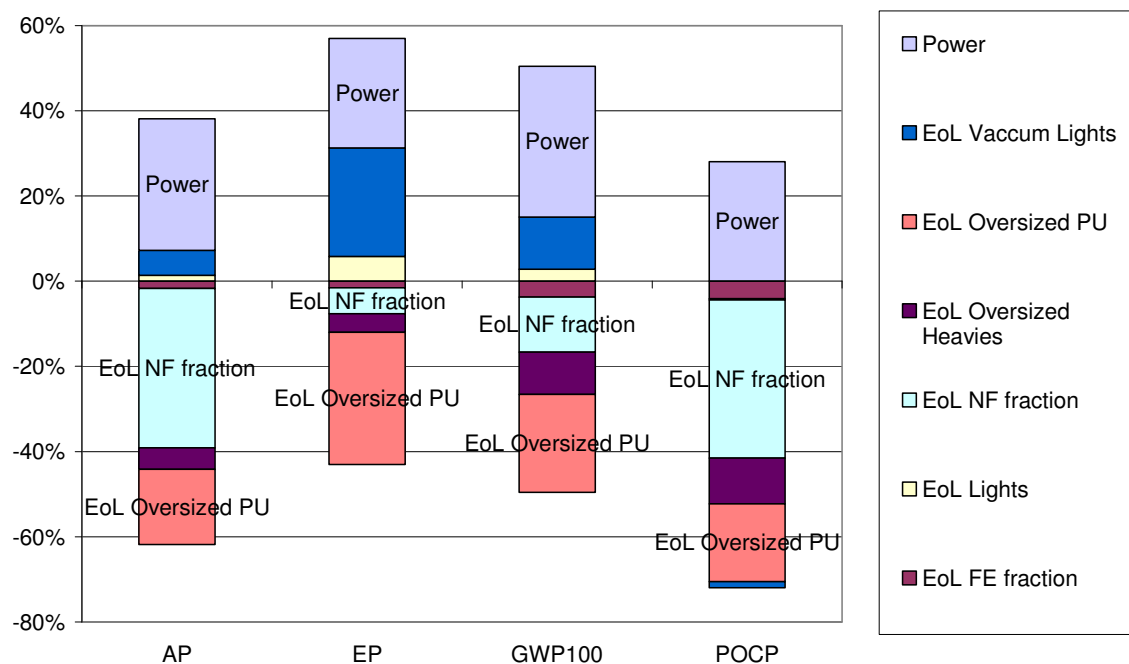


### Mechanical Separation Plant

The used power for the Mechanical Separation Plant dominates the burden of the impact category POCP. The energy recovery of “Vacuum Lights” and “Lights” contribute also to the impact categories AP, EP and GWP100. This is based on the fact that the efficiency of the production of thermal energy and electricity of the energy recovery process is less compared to the production of thermal energy from natural gas and electricity based on the grid mix. Therefore the “CO<sub>2</sub>-benefits” are less compared to the CO<sub>2</sub>-emissions of the energy recovery process. The output of the energy recovery process is approximately 90% thermal energy and 10 % electricity. The overall thermal efficiency is approximately 75%. The relatively low thermal efficiency, compared to the 94% of efficiency of the production of thermal energy from natural gas, is due to losses and the internal need of thermal energy and electricity to run the process. The energy recovery therefore only shows advantages for primary energy demand.

The avoided production of materials due to material substitution by ferrous metal, non-ferrous metals and PU show benefits regarding all analyzed impact categories.

For detailed information on the absolute values see Appendix B 1.



**Figure 5-5: Detailed Impact categories (Mechanical Separation Plant)**

The huge benefit shown for AP and POCP in Figure 5-5 related to the NF fraction is based on the avoided SO<sub>2</sub> emission during copper production. The saved NO<sub>x</sub> emissions to air and the avoided nitrate, nitrogen and phosphate emissions to water are the reason for the benefit related to the substitution of PU foam.

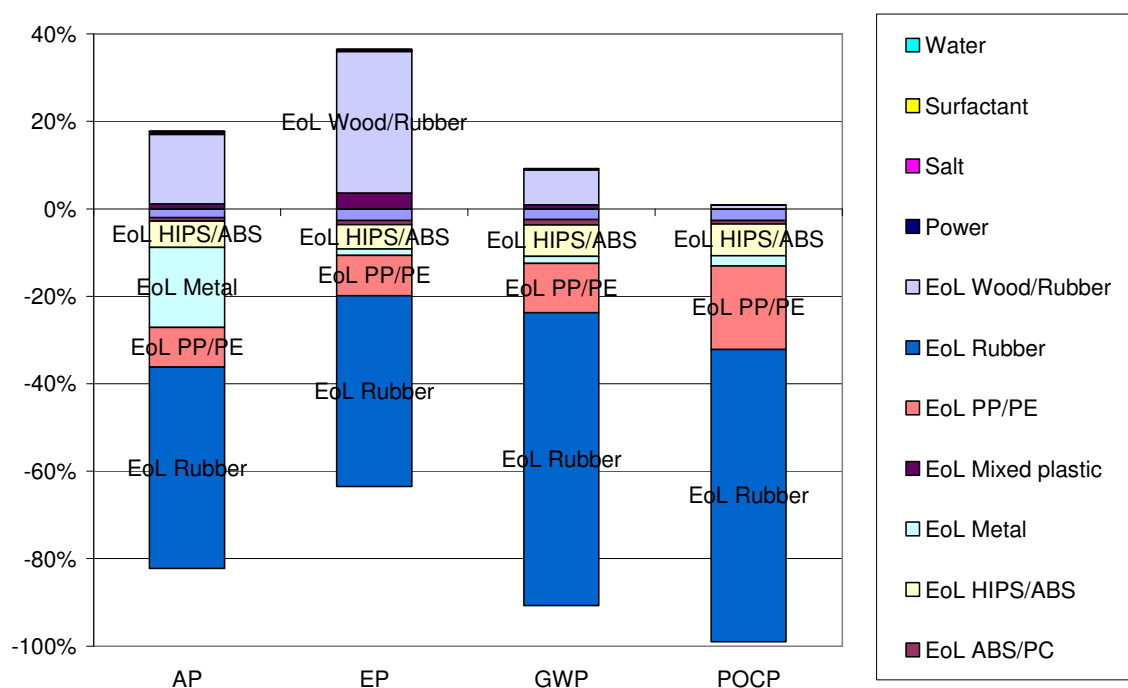




### Froth Flotation Plant

The burdens of the Froth Flotation Plant for AP, EP and GWP are dominated by the fractions handled by energy recovery (Wood/Rubber and mixed plastic fraction). The contribution of the consumed power and auxiliary materials (salt, water and surfactant) are negligible. The wood and rubber mixture that is separated from the PP/PE product is placing an AP and EP penalties on the Froth Flotation process due to the fact that the efficiency of the production of thermal energy and electricity of the energy recovery process is less compared to the production of thermal energy from natural gas and electricity based on the grid mix. (See former paragraph)

For detailed information on the absolute values see Appendix B 2.



**Figure 5-6: Detailed Impact categories (Froth Flotation Plant) CO<sub>2</sub> emissions**

The running of the Mechanical separation plant causes 311 kg CO<sub>2</sub> emissions for 40,000 lb shredder residue processed. This is related to the power consumption and the fact that the energy recovery causes higher CO<sub>2</sub> emission than avoided due to substituted power production. The handling of the separated fractions by the Froth Flotation shows a benefit of 7628 kg CO<sub>2</sub> emissions per 40,000 lb of shredder residue processed.

**Table 5-4: CO<sub>2</sub> emissions in kg for the ARGONNE plant**

	Total	Mechanical Separation Plant	Froth Flotation Plant
CO <sub>2</sub> emission [kg]	-7628	311	-7939

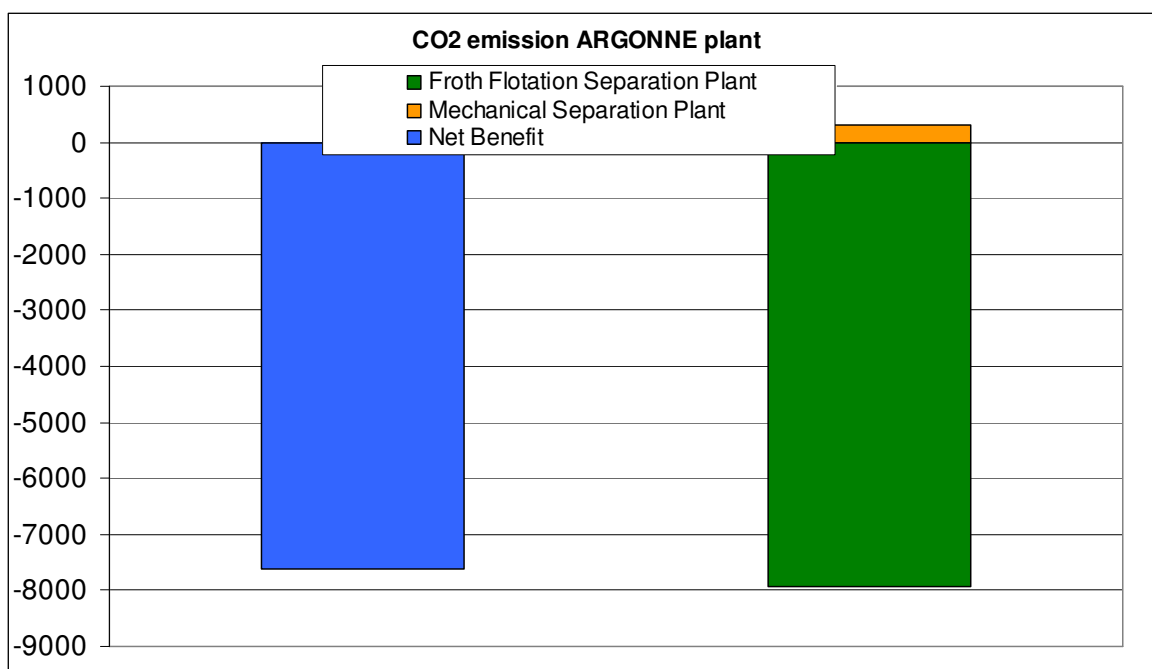


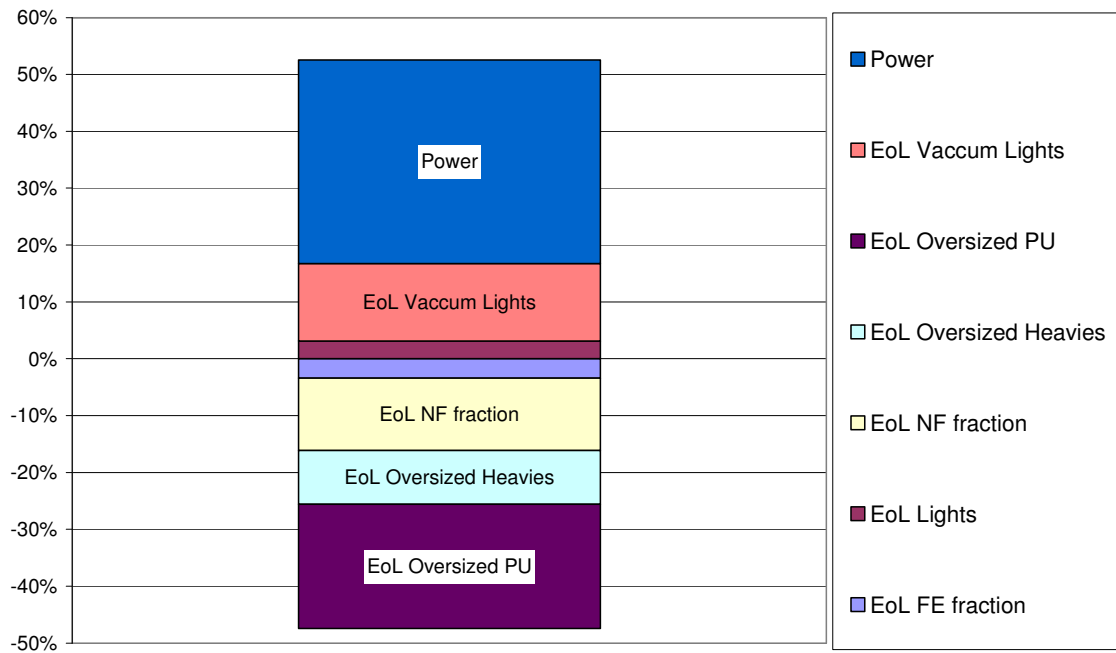
Figure 5-7: CO<sub>2</sub>-emissions (Argonne plant)



### Mechanical Separation Plant

In total there is no benefit of CO<sub>2</sub> emissions resulting from the Mechanical Separation Plant. The amount of CO<sub>2</sub> emitted by the used power and the energy recovery of the Lights and the Vacuum Lights is higher than the credit of CO<sub>2</sub> emissions related to the handling of the other fractions.

For detailed information on the absolute values see Appendix B 1.



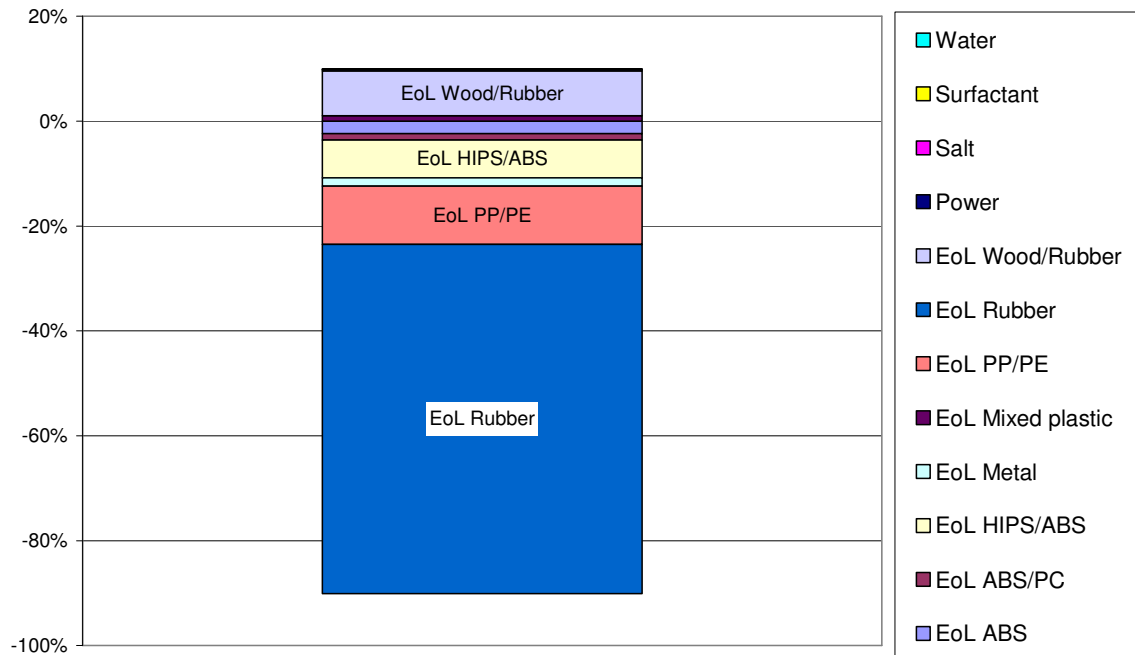
**Figure 5-8: Detailed CO<sub>2</sub>-emissions (Mechanical Separation Plant)**



### Froth Flotation Plant

The credits of the Froth Flotation Plant are dominated by the fraction rubber concentrate product (~70%), PP/PE product (~10%) and HIPS/ABS product (~10%). “Rubber” shows the highest benefit. This is mainly related to the fact the quantitative mass value of the separated “rubber approx. three times than the next fraction which is substituting another polymer (PP/PE).

For detailed information on the absolute values see Appendix B 2.



**Figure 5-9: Detailed CO<sub>2</sub>-emissions (Froth Flotation Plant)**



## 6 Results of the comparison of the Argonne process with the Salyp process<sup>7</sup>

### 6.1 LCI model of Salyp process

The Salyp shredder residue separation process is a technology separating various material fractions from shredder residue. The separated fractions can be given to the following types of waste residue treatment / recycling processes like:

- thermal incineration for energy recovery,
- material recycling or
- direct substitution of materials in other processes, e.g. organics substituting energy feedstock in cement kiln based on the lower calorific value

The goal of the technology is to separate the valuable material fractions within a purity which meets the requirements for further usage (closed loop recycling).

As the plastic separation process (Dorado process) as part of the Salyp facilities did not achieve the necessary purity to meet the requirements for product applications, the mixed plastic and PUR foam stream has been handled by energy recovery.

### 6.2 Comparative results

The basis for the comparison of the ARGONNE process with the Salyp process is the same material composition. The amount of the shredder residue is for both process 1 kg input. The used material composition of the starting shredder residue is displayed in Table 6-1. The given material composition is scaled for the comparison based on one kg.

The analysis of the comparison is limited to the primary energy demand, CO<sub>2</sub> emissions and selected impact categories (AP, EP, GWP100, and POCP).

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<sup>7</sup> For more information on the Salyp process, please see Life Cycle Inventory (LCI) of the Salyp SR separation process under VRP PO #722

**Table 6-1: Material composition of the starting shredder residue**

<b>Fraction</b>	<b>Mass of Starting Shredder Residue in %</b>
Polypropylene	3,87
Polypropylene (filled)	0,44
ABS	2,09
Polyethylene	3,30
Polystyrene	0,85
Nylon	0,98
Polyvinylchloride	1,79
PPO	0,22
PC/ABS	0,10
Polycarbonate	1,67
Trace Plastic	0,52
Unidentified Plastic	0,69
Rubber	13,44
Rigid Polyurethane	4,48
Flexible Polyurethane	9,61
Wood	0,71
Copper	1,06
Brass	0,12
Ferrous (steel)	17,04
Aluminium	5,24
Rocks	5,50
Polyethylene terephthalate fibers	18,66
Glass	4,27
Thermoset plastics	3,34
<b>Total</b>	<b>100,00</b>

The following table gives an overview of the inputs and outputs energy flows respectively the input and output mass flows.



**Table 6-2: Inputs and Outputs energy and mass flows – Comparison ARGONNE Process with Salyp Process (based on 1 kg shredder residue)**

per kg processes SR	ARGONNE Process	Salyp Process	Comment
<u>Inputs total</u>			
Power	0.471 MJ	0.262 MJ	Argonne: Shredder contributes with 44% to the overall energy consumption, Granulator with 46%
Steam	-	0.004 kg	
<u>Outputs Mechanical Separation</u>			
Dust	0.0479 kg	0.11 kg	Salyp: 11 wt-% of processes SR
FE metals	0.0353 kg	0.04842 kg	
Energy recovery goods	0.0604 kg	-	
Landfill goods	0.0521 kg	-	
NF metals	0.0464 kg	0.05785 kg	
Organics for recovery	0.3082 kg	0.3961 kg	Salyp: Handled by energy recovery
Fines and Fibers	0.4497 kg	0.3502 kg	Salyp: Handled by energy recovery
Glass for recovery	-	0.038 kg	
<u>Outputs Froth Flotation</u>			
PP/PE product	0.0527 kg	-	Substitution of 100% PP (loss factor = 85%)
Wood/Rubber product	0.0574 kg	-	100% Energy recovery
HIPS/ABS product	0.0238 kg	-	Substitution of 100% low PS (loss factor 90%)
ABS product	0.0057 kg	-	Substitution of 100% ABS (loss factor 90%)
Mixed plastic product	0.0063 kg	-	100% Energy recovery
ABS/PC product	0.00197 kg	-	Substitution of 50% ABS / 50% PC (loss factor 90%)
Rubber product	0.1525 kg	-	Substitution of 100% EPDM (loss factor)
Metal product	0.0078 kg	-	Substitution of 25% Steel / 22.5% Aluminium / 52.5% Copper



### 6.2.1 Discussion in inventory level (emissions)

In Table 6-3 the analyzed emissions are presented which are depicted in the following graphs. Except for NO<sub>x</sub> emission the Argonne process gets credits for CO<sub>2</sub>, SO<sub>2</sub> and VOC emissions. The Salyp process shows only an overall benefit for SO<sub>2</sub> and VOC emissions.

**Table 6-3: Comparison of ARGONNE process – Salyp process (CO<sub>2</sub> emissions)**

	<b>ARGONNE process (mechanical and Froth Flotation)</b>	<b>Salyp process</b>
CO <sub>2</sub> emission [kg]	-0.5499	0.4141
SO <sub>2</sub> emission [kg]	-0.0028	-0.011
NO <sub>x</sub> emission [kg]	0.0002	0.0054
VOC emission [kg]	-0.0055	-0.0022

As displayed in Figure 6-1 the recovery of the rubber is the most dominating fraction of the Argonne process when analyzing CO<sub>2</sub> emissions. Due to the high mass amount of this fraction the overall results in a credit for CO<sub>2</sub> emissions. The Salyp process is dominated by the energy recovery of the PUR and plastic mix fraction. The highest amount of credit is given for the glass recycling which is related to the silver<sup>8</sup> recovered from the glass fraction.

<sup>8</sup> Analysis of the glass fraction recovered by the Salyp process showed that an amount of silver has been attached to the glass which was worth recovering from an economic point of view. It has been assumed that the origin of the silver has been electronics, connectors etc. Should the silver not be recovered from the glass fraction, it would be handled as waste for landfill and not result in ecological benefits.



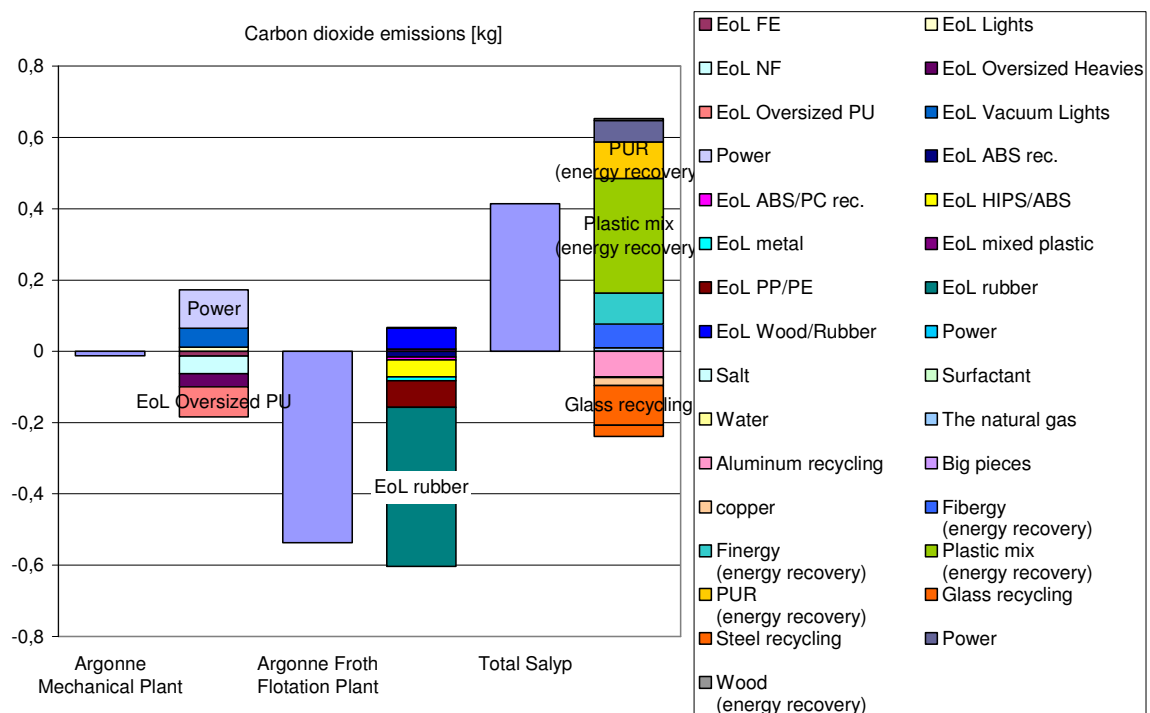
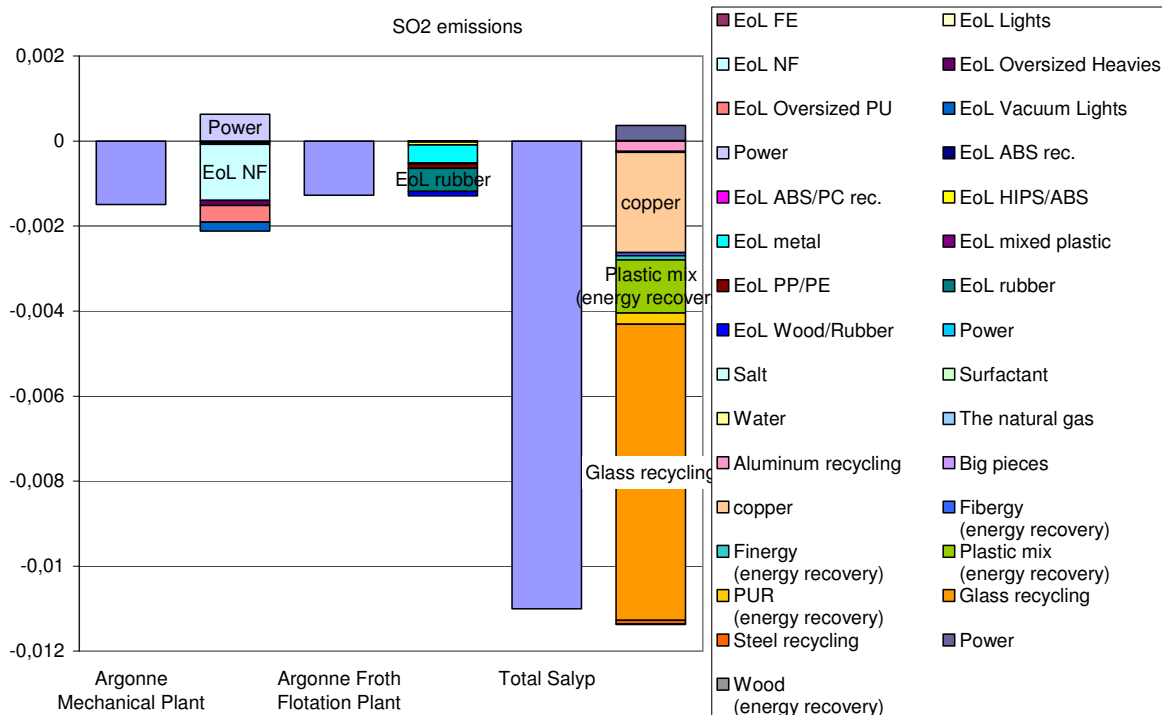


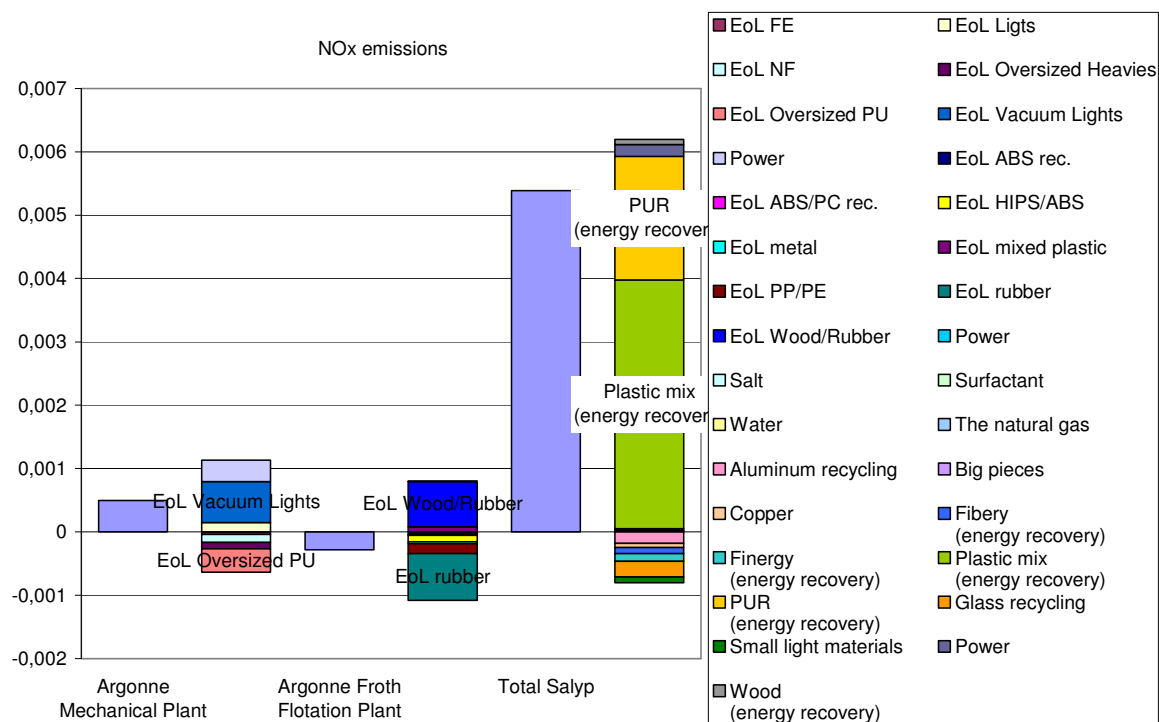
Figure 6-1: kg Carbon dioxide emissions per 1 kg shredder residue

When analyzing the SO<sub>2</sub> emissions, the absolute benefit for the Mechanical Separation Plant and the Froth Flotation Plant is almost the same. While the credit of the Mechanical Separation Plant is dominated by the recycling of the NF metals, the Froth Flotation Plant is dominated by the rubber and metal product recovery. The Salyp process gives credits for copper recovery, plastic mix recovery and the glass recovery. As shown in Figure 6-2 the glass recycling is contributing the highest share. This is mainly related to the avoided SO<sub>2</sub> intensive silver production by the recycling of the silver. The fact that the credits for SO<sub>2</sub> emissions related to copper are higher for the Salyp process than for Argonne is caused by the high percentage of copper (approx. 2/3) which is land filled as part of the fines.

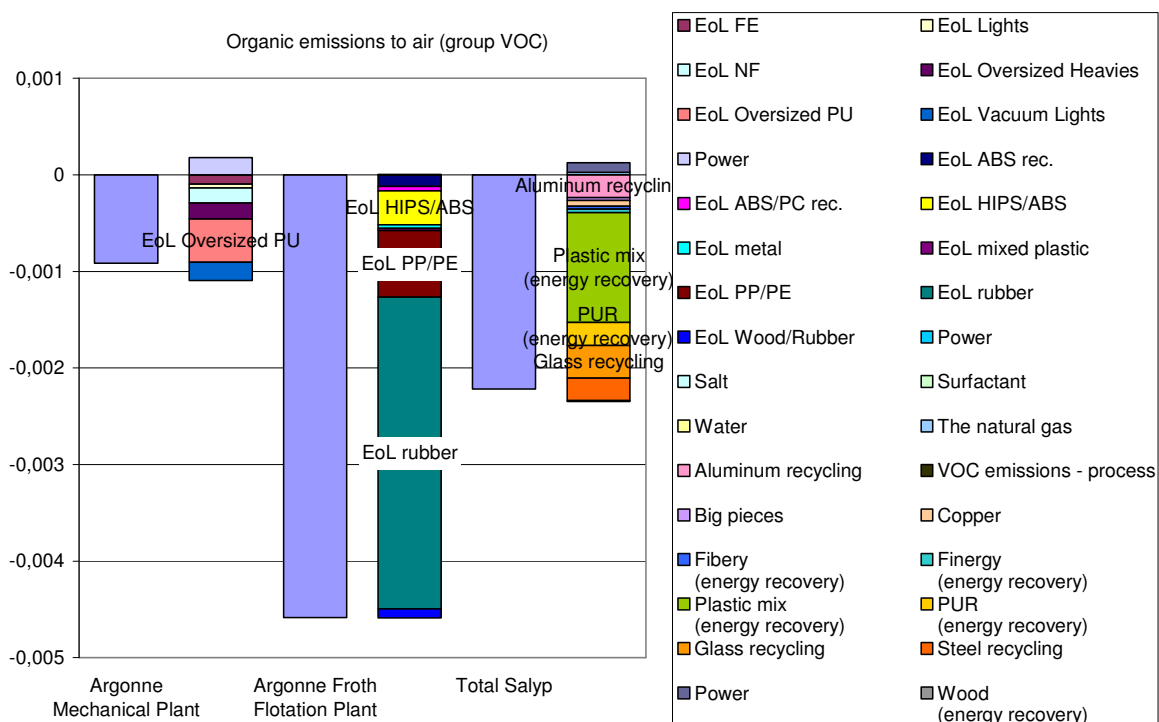


**Figure 6-2: kg Sulfur dioxide emissions per 1 kg shredder residue**

As amount of NO<sub>x</sub> emissions caused by the Mechanical Separation Plant is higher than the credit given in the Froth Flotation Plant, the Argonne process results in a positive value for the NO<sub>x</sub> emissions. This effect is mainly caused by the energy recovery of the organic fractions which do not meet the requirements to be used for material substitution and the power consumption. As shown in Figure 7-4 the highest contributions to the NO<sub>x</sub> emissions when analyzing the Salyp process are also caused by the energy recovery of the organic fractions, e.g. PUR and plastic mix.



**Figure 6-3: kg Nitrogen oxide emissions per 1 kg shredder residue**



**Figure 6-4: kg Organic emissions to air (group VOC) per 1 kg shredder residue**

All three processes result in overall credits for VOC emissions, see Figure 7-5.



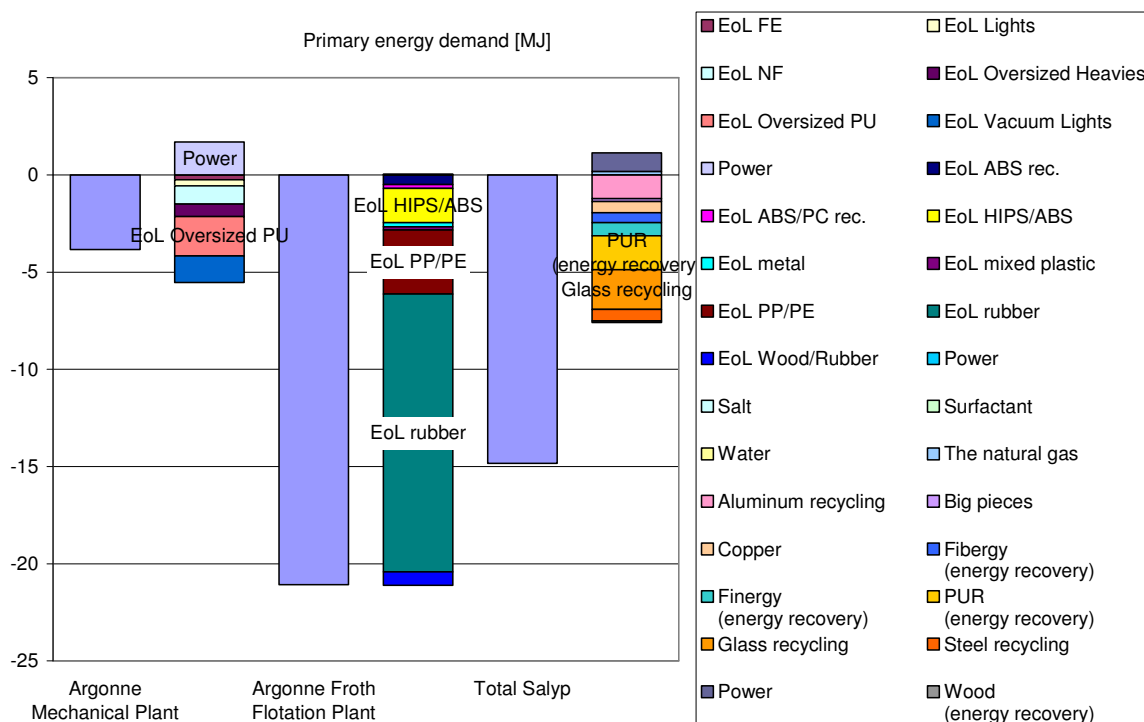
### 6.2.2 Discussion of impact categories

In Table 6-4 the results for primary energy demand are given, while the results for the impact categories are presented in Table 6-5. The Argonne process shows for all analyzed impacts benefits and the handling of the SR by the Salyp process only results in overall benefits for primary energy demand, AP and POCP.

The benefits for the ARGONNE process are mainly related to the Froth Flotation/ product substitution.

**Table 6-4: Comparison of ARGONNE process – Salyp process (Primary energy demand)**

	<b>ARGONNE process (mechanical and Froth Flotation)</b>	<b>Salyp process</b>
Crude oil [MJ]	-12.33	-1.02
Hard coal [MJ]	-1.51	-2.86
Lignite [MJ]	-0.55	-0.15
Natural gas [MJ]	-9.61	-8.82
Uranium [MJ]	-0.96	-1.39
Renewable energy [MJ]	-0.33	-0.60



**Figure 6-5: MJ Primary energy demand (renewable and non-renewable) per 1 kg shredder residue**

Figure 6-5 shows the primary energy demand for the overall process and broken down for each separated fraction/ end energy demand describing the specific benefits/ burdens. Both technologies show overall saving of primary energy.

The fractions Oversized Polyurethane foam and Vacuum Lights dominate the benefit of the Mechanical Separation Plant and the fractions recovered PP/PE and recycling rubber dominate the Froth Flotation Plant. The Salyp process is dominated by the credits for PUR (energy recovery) and Glass recycling (recovery of silver).

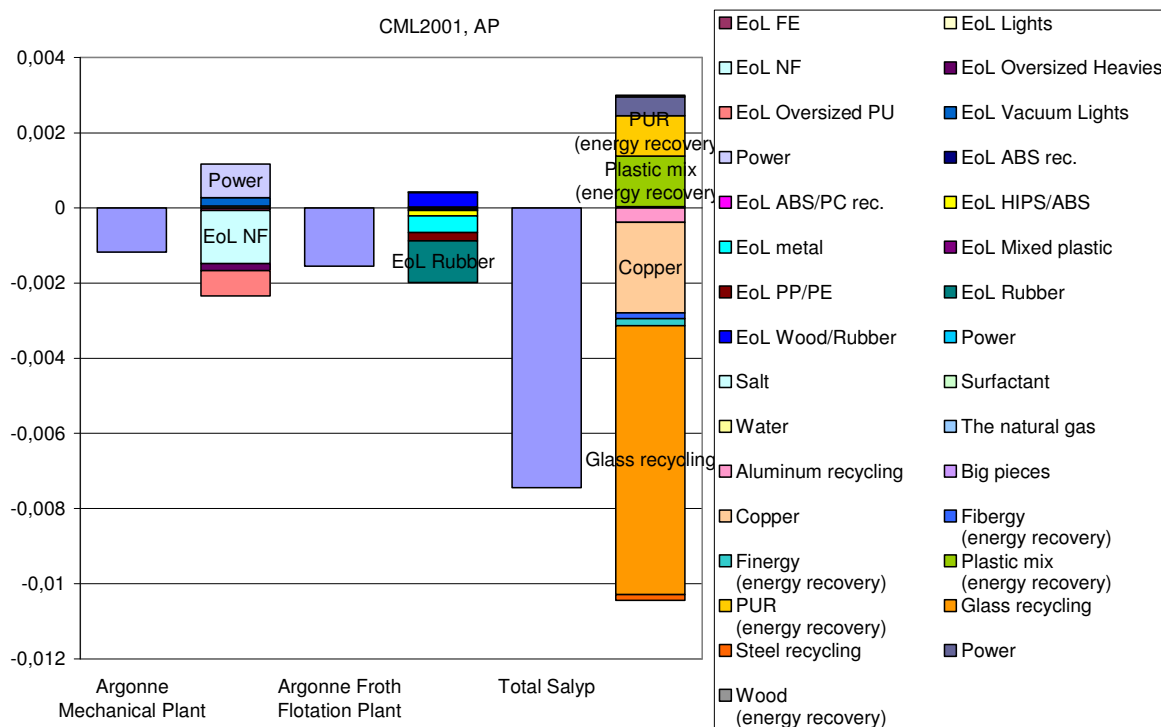
In the following figures the selected impact categories are analyzed.

**Table 6-5: Comparison of Argonne process – Salyp process (Impact categories)**

	ARGONNE process (mechanical and Froth Flotation)	Salyp process
AP [kg SO <sub>2</sub> -Equiv.]	-0.0027	-0.0075
EP [kg Phosphate-Equiv.]	-5.0E-5	6.7E-4
GWP100 [kg CO <sub>2</sub> -Equiv.]	-0.614	0.3903
POCP [kg Ethene-Equiv.]	-1.2E-3	0.0057



Both steps of the Argonne process give credits for the AP and the POCP. Considering EP and GWP100 only the Froth Flotation Plant shows a benefit. The negative effect on EP and GWP of the Salyp process are mainly related to the energy recovery of PUR and plastic mix. The specific shares of each fraction (credit or benefit) are presented in Figure 6-6 to Figure 6-9 .



**Figure 6-6:** kg SO<sub>2</sub>-Equiv. Acidification Potential (CML2001, AP) per 1 kg shredder residue

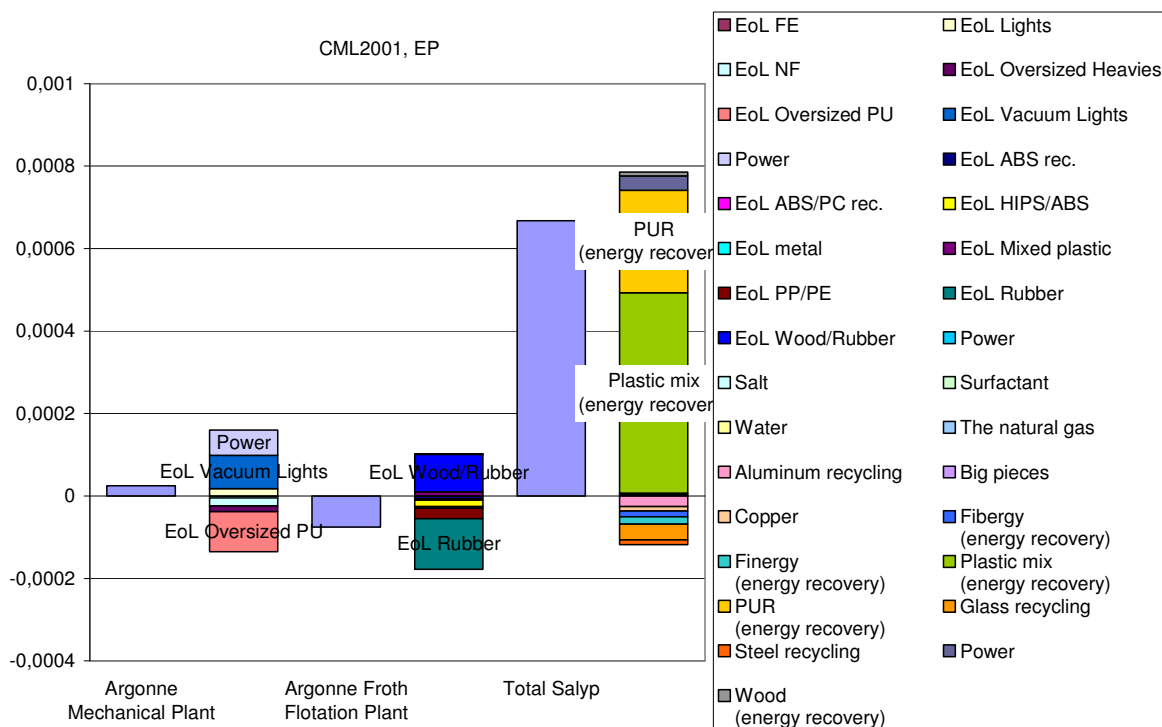


Figure 6-7: kg Phosphate-Equiv. Eutrophication Potential (CML2001, EP) per 1 kg shredder residue

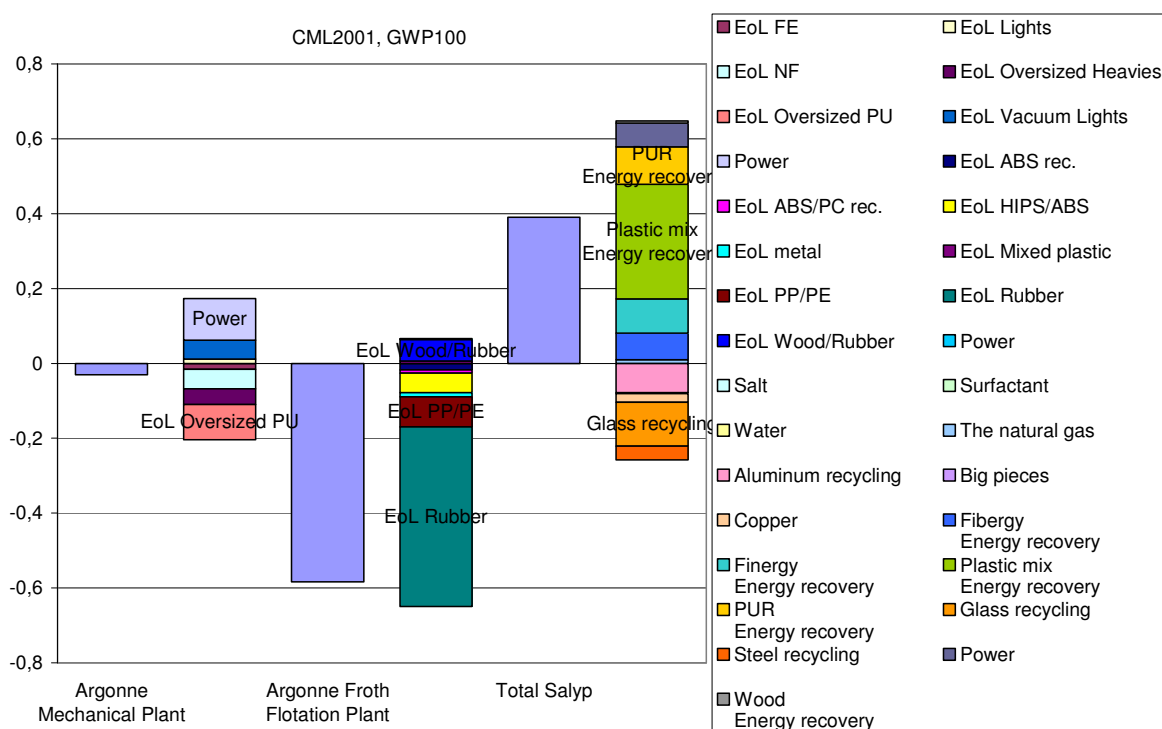
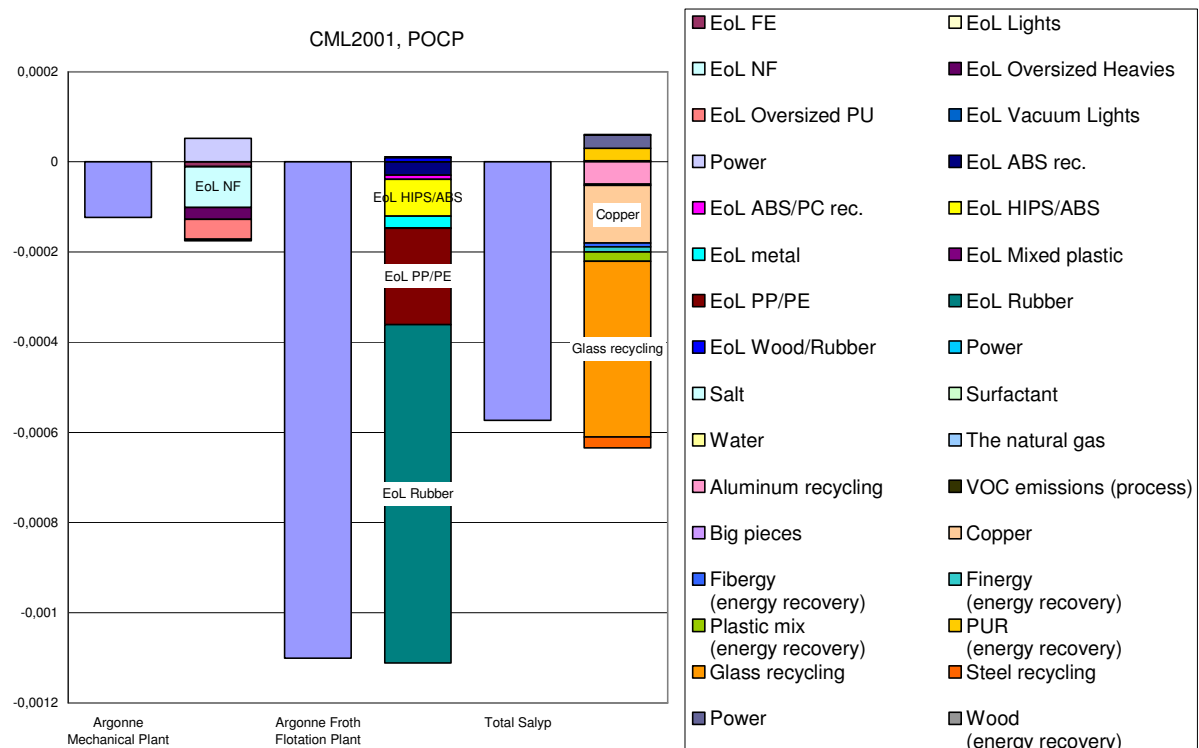


Figure 6-8: kg CO2-Equiv. Global Warming Potential (CML2001, GWP100) per 1 kg shredder residue



**Figure 6-9: kg Ethene-Equiv. Photochem. Ozone Creation Potential (CML2001, POCP) per 1 kg shredder residue**

### 6.2.3 Summary comparison ARGONNE – Salyp

The comparison of the two technologies showed, that both processes show benefits for primary energy demand, specific impact categories and specific emissions. The environmental benefits are higher for the Argonne process compared to the Salyp process except for the impact category AP and SO<sub>2</sub> emissions. This effect is related to the silver recovery which has been detected as part of the glass fraction separated by the Salyp process.

Negative effects are either caused by the consumption of power or the energy recovery of organic fractions which do not meet the requirements to be used in other applications.

The comparison clearly showed that material recycling/ substitution should be preferred over energy recovery. Therefore the mixed plastic fraction of the Salyp process should be either separated further into specific polymer fractions which could be used for material recycling or applications for the mixed plastic fraction should be identified. This would significantly improve the overall environmental profile of the Salyp process.

As the only fractions cause negative environmental impact for selected emissions/ impact categories are the ones handled by energy recovery, the efforts should be regarding alternative scenarios, e.g. applications.

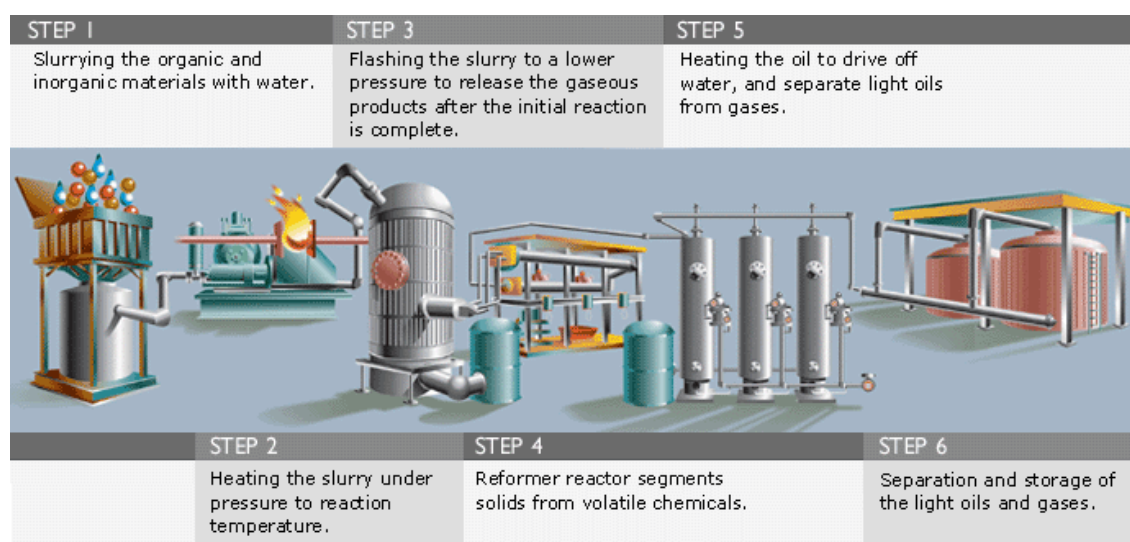


## 7 Results of the comparison with the CWT process<sup>9</sup>

### 7.1 LCI model of CWT process

The thermal conversion process (TCP) of CWT converts organic material and hydrocarbon into fuels and other valuable products using water, heat and pressure. The process can be described as a “replica” of the natural geothermal process, which converts organic and inorganic wastes. The CWT process consists of three main steps:

- Pulping the feedstock and heating the slurry under pressure (step 1 and 2 shown in Figure 7-1)  $\Rightarrow$  slurry reaches 1<sup>st</sup> stage reaction status; process temperature between 392°F (200°C) to 572°F (300°C)
- Flashing of slurry  $\Rightarrow$  separating 1<sup>st</sup> stage oil from water
- Heating 1<sup>st</sup> stage oil to temperature of about 932°F (500°C)  $\Rightarrow$  cracking of 1<sup>st</sup> stage oil into hydrocarbons



**Figure 7-1 Outline CWT thermal conversion process<sup>10</sup>**

All produced gases can be used internally to produce the heat, steam, or electricity that is needed for running the process. In the event that not all of the gases are needed for internal energy production, they could be used for electricity generation, which might be fed into the regional grid.

The individual steps of the CWT thermal conversion process have been developed by other industries (oil and gas processing industry) and used for years.

Besides the emissions coming from the gas turbine, which is used for electricity and steam generation, no emissions to atmosphere occur from the process.

<sup>9</sup> For more information on the CWT process, please see Life Cycle Inventory (LCI) of the CWT Thermal Conversion Process under PO #722 Amend A

<sup>10</sup> Source: <http://www.changingworldtech.com/what/index.asp>



Within the scenario used for the comparison in this study the TCP-40 oil and carbon fraction is handled as input for end energy generation replacing the non renewable resources crude oil and hard coal. The substitution of crude oil with TCP-40 oil and hard coal with the carbon fraction has been done under the assumption that the properties of TCP-40 oil and the carbon fraction meet the user's specifications. The assigned benefits were calculated based on the environmental burdens, which would occur if the "substituted" material would have been used.

## 7.2 Comparative results

The comparison of the ARGONNE and the CWT process is based on the material composition of polymer concentrate as displayed in Table 7-1. It is assumed, that there is a mechanical separation prior to the CWT process handling big pieces, most of the ferrous and non-ferrous metals. The comparative results include the handling of the polymer concentrate once in the Argonne Froth Flotation plant and second in the CWT processes. It is assumed that the mechanical separation is identical for both processes.

**Table 7-1: Material composition of the polymer concentrate**

<b>Fraction</b>	<b>Mass of polymer concentrate in %</b>
ABS	5,89
Aluminium	0,52
Copper	1,19
Ferrous metals	0,56
Flexible PU	0,24
Nylon	2,59
PC	4,78
PC/ABS alloys	0,28
Polyethylene	8,68
PET fibers	0,68
Polypropylene	9,72
Polypropylene (filled)	1,23
PPO	0,60
PS	2,23
Rigid PU	12,47
PVC	5,26
Rocks	0,32
Rubber	37,36
Trace plastics	1,47
UI plastics	1,91
Wood	2,07
<b>Total</b>	<b>100,00</b>

The following table gives an overview of the input and output flows (end energy and material) respectively the input and output mass flows related to 1 kg material input as defined in Table 7-1.



**Table 7-2: Inputs and Outputs energy and mass flows – Comparison ARGONNE Process with CWT Process (based on 1 kg polymer concentrate)**

per kg processes SR	Argonne Process	CWT Process	Comment
<i>Inputs total</i>			
Power	0.0034921 MJ	0.01287 MJ	CWT – produced internally
Base	-	0.0773 kg	Depending on chlorine content
<i>Outputs Froth Flotation</i>			
Waste water	-	0.15531 kg	Amount of waste water depends on moisture content; additional water is added to the process
Fuel gas	-	0.14251 kg	Depend on organic content of SR
TCP-40 oil	-	0.53021 kg	Depend on organic content of SR
Carbon	-	0.28334 kg	Depend on organic content of SR
FE metals	-	0.0056 kg	
NF metals	-	0.01712 kg	
Solids	-	0.075927 kg	
PP/PE product	0.1708 kg		Substitution of 100% PP (loss factor = 85%)
Wood/Rubber product	0.18623 kg		Substitution of 100% Energy recovery
HIPS/ABS product	0.077139 kg		Substitution of 100% low PS (loss factor = 90%)
ABS product	0.01857 kg		Substitution of 100% ABS (loss factor = 90%)
Mixed plastic product	0.020311 kg		Substitution of 100% Energy recovery
ABS/PC product	0.0063766 kg		Substitution of 50% ABS / 50% PC (loss factor = 90%)
Rubber product	0.4946 kg		Substitution of 100% EPDM (loss factor 90%)
Metal product	0.025489 kg		Substitution of 25% Steel / 22.5% Aluminium / 52.5% Copper (loss factor = 90%)

### 7.2.1 Discussion in inventory level (emissions)

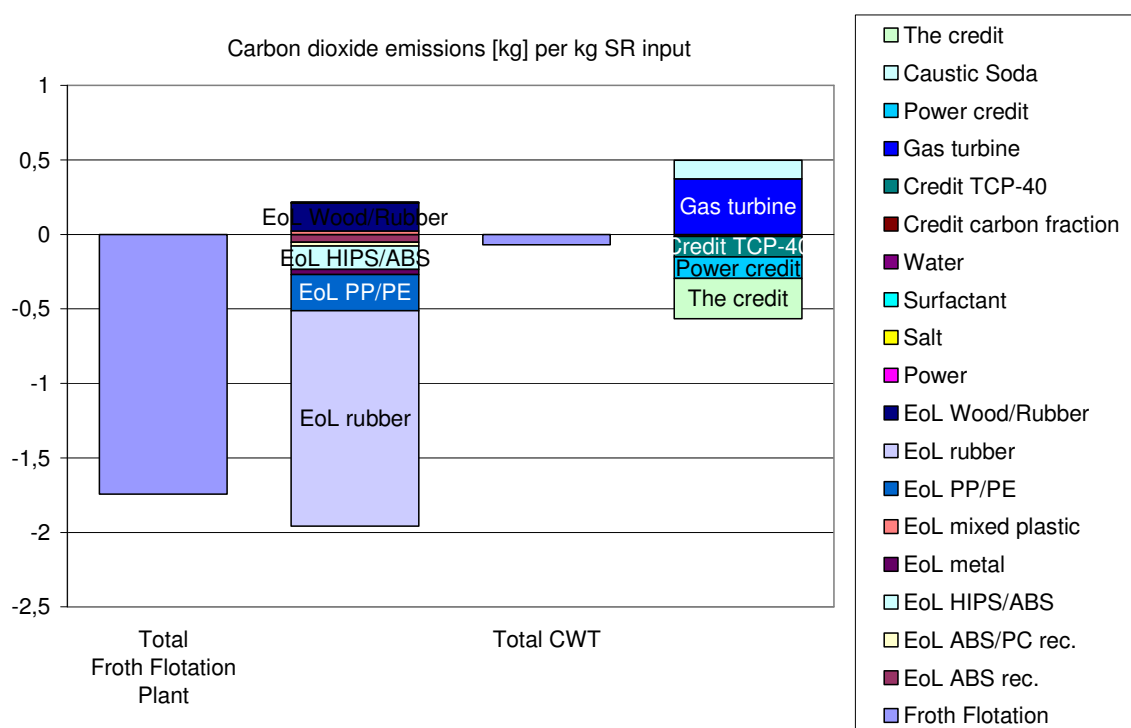
Both technologies show overall benefits for the discussed emissions, while the Argonne show higher overall savings except for NO<sub>x</sub> which is related to the NO<sub>x</sub> emissions related to the energy recovery of the wood/ rubber and mixed plastic fraction.

**Table 7-3: Comparison of Argonne process – CWT process (CO<sub>2</sub> emissions)**

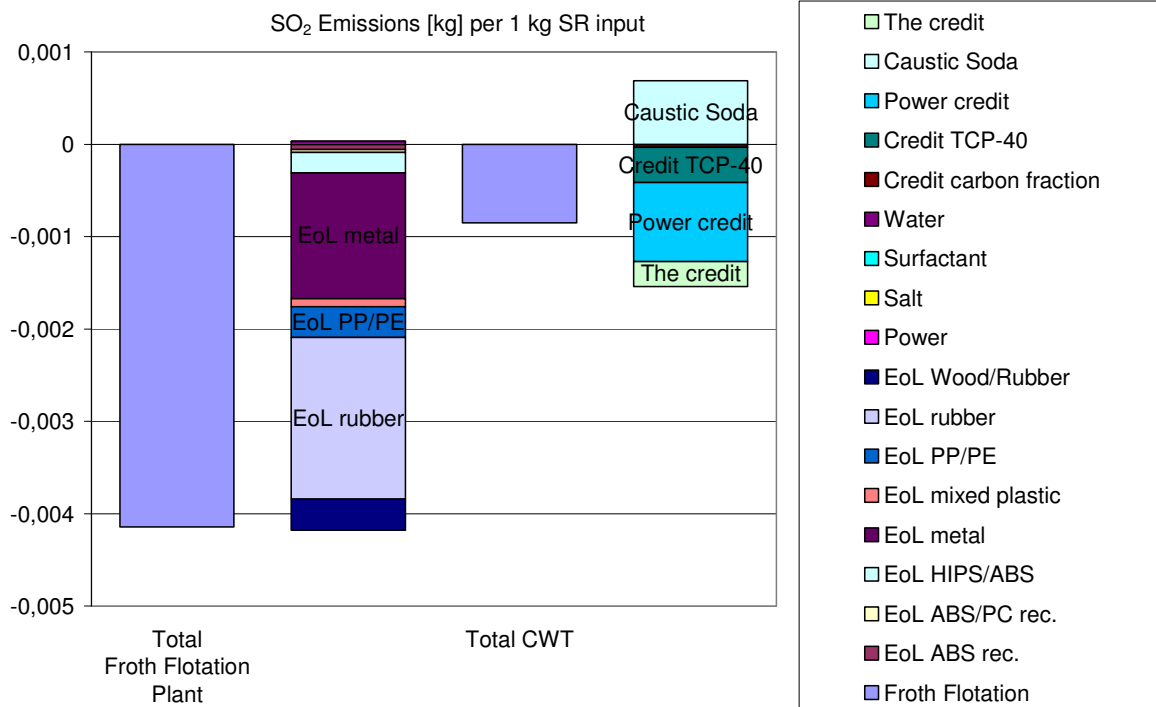
	ARGONNE process (Froth Flotation)	CWT process
CO <sub>2</sub> emission [kg]	-1.74	-0.07
SO <sub>2</sub> emission [kg]	-4.1E-3	-8.5E-4
NO <sub>x</sub> emission [kg]	-9.2E-4	-2.4E-3
VOC emission [kg]	-0.015	-6.9E-3

The usage of the Argonne process gives a benefit of 1.7 kg CO<sub>2</sub> emissions. The usage of the CWT process gives only a credit of 0.07 kg CO<sub>2</sub> emissions.

The recovery of the rubber is the most dominating fraction of the Argonne process for giving credits. Due to the amount of this fraction the overall results is a credit for CO<sub>2</sub> emissions. The CO<sub>2</sub> emissions of the CWT process are calculated by the sum of the credits of the power and the thermal energy and the burden of the gas turbine.

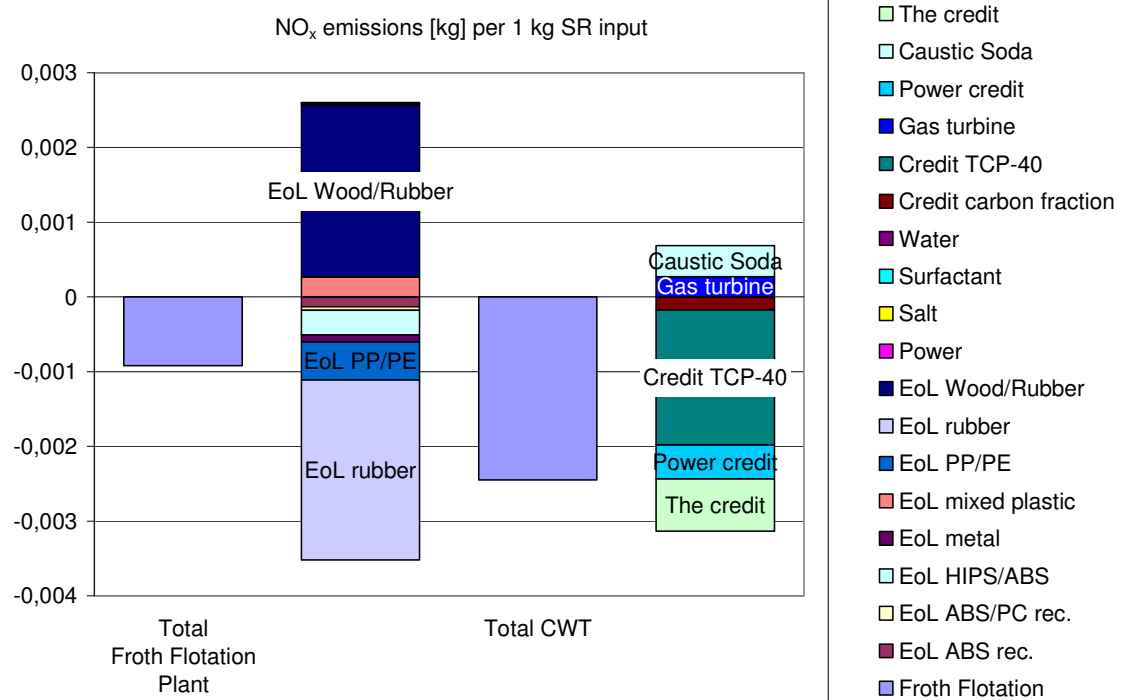
**Figure 7-2: kg Carbon dioxide emissions per 1 kg of shredder residue**

The credit of the Froth Flotation Plant consists mainly of the credit given by the rubber product recovery.



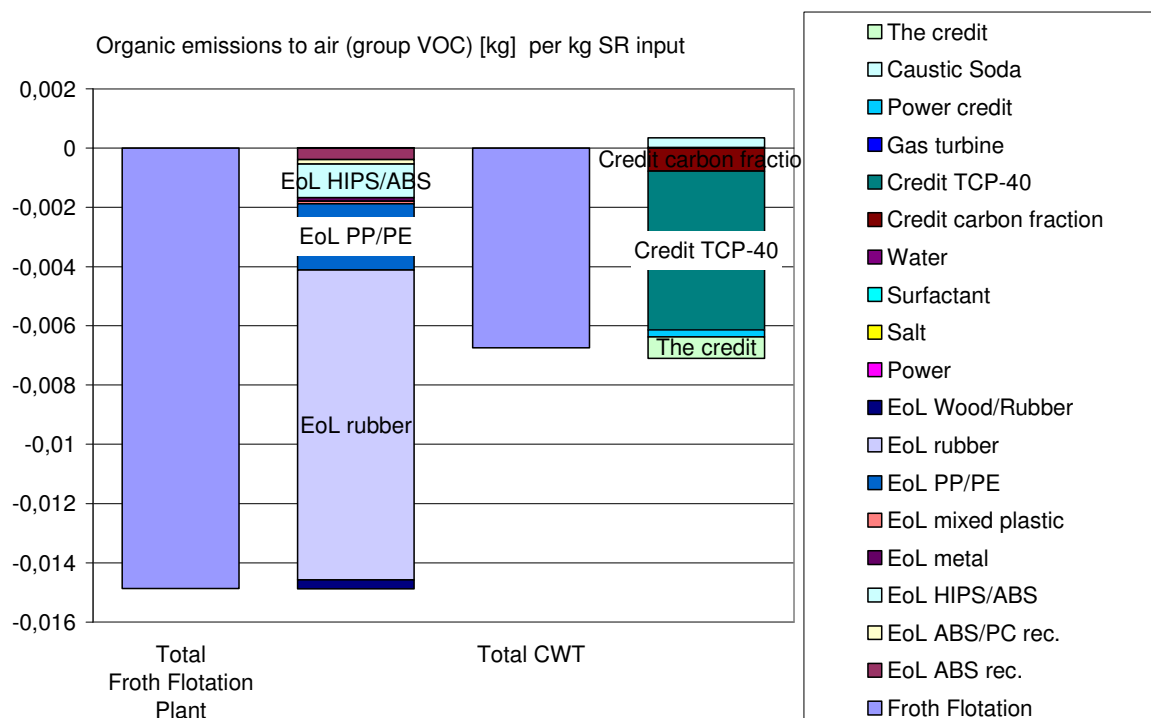
**Figure 7-3: kg Sulfur dioxide emissions per 1 kg of shredder residue**

As shown on Figure 7-3 the share related to separated metals is much higher than for the other emissions analyzed. This related to the substituted copper which has a high SO<sub>2</sub> emissions compared with the other substituted metals/ polymers. The same effect can be seen for the acidification potential, see Figure 7-7. As the produced fuel gas of the CWT process contains no sulfur, no SO<sub>2</sub> emissions are caused by the gas turbine.



**Figure 7-4: kg Nitrogen oxide emissions per 1 kg of shredder residue**

The high amount of VOC emissions credits in the froth flotation process is due to the product recovery of the rubber.



**Figure 7-5: kg Organic emissions to air (group VOC) per 1 kg of shredder residue**

## 7.2.2 Discussion of impact categories

The comparison of the two technologies has been performed for primary energy demand, selected emissions ( $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{NO}_x$  and VOC) and impact categories (AP, EP, GWP100 and POCP).

As shown in Table 7-4 and Figure 7-6 the Argonne process shows higher benefits than the CWT process for all energy resources. This is based on the fact, that the separated metals most of the organics of the ARGONNE process are replacing materials while the produced TCP-40 oil and the carbon fraction of the CWT process are used as energy input of energy production replacing crude oil or hard coal and the metals are land filled and the primary energy demand saved for substituting polymers is higher than substituting crude oil or hard coal.

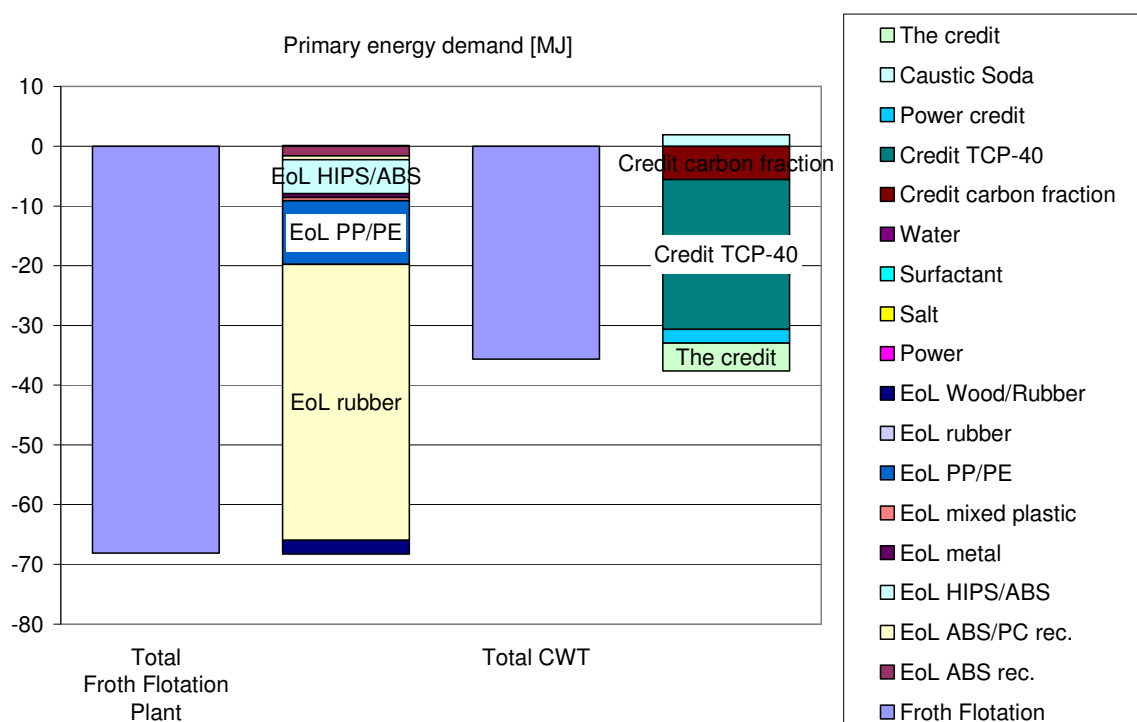
**Table 7-4: Comparison of Argonne process – CWT process (Primary energy demand)**

	ARGONNE process (Froth Flotation)	CWT process
Crude oil [MJ]	-37.5	-24.1
Hard coal [MJ]	-2.2	-5.7
Lignite [MJ]	-1.5	-0.09
Natural gas [MJ]	-24.2	-5.6
Uranium [MJ]	-2.8	-0.21
Renewable energy [MJ]	-0.26	-0.01





As shown in the next graph, there is a benefit for all produced fractions when analyzing primary energy demand. Only the used energy for running the Argonne process and the needed caustic soda for the CWT process contribute to the primary energy demand.

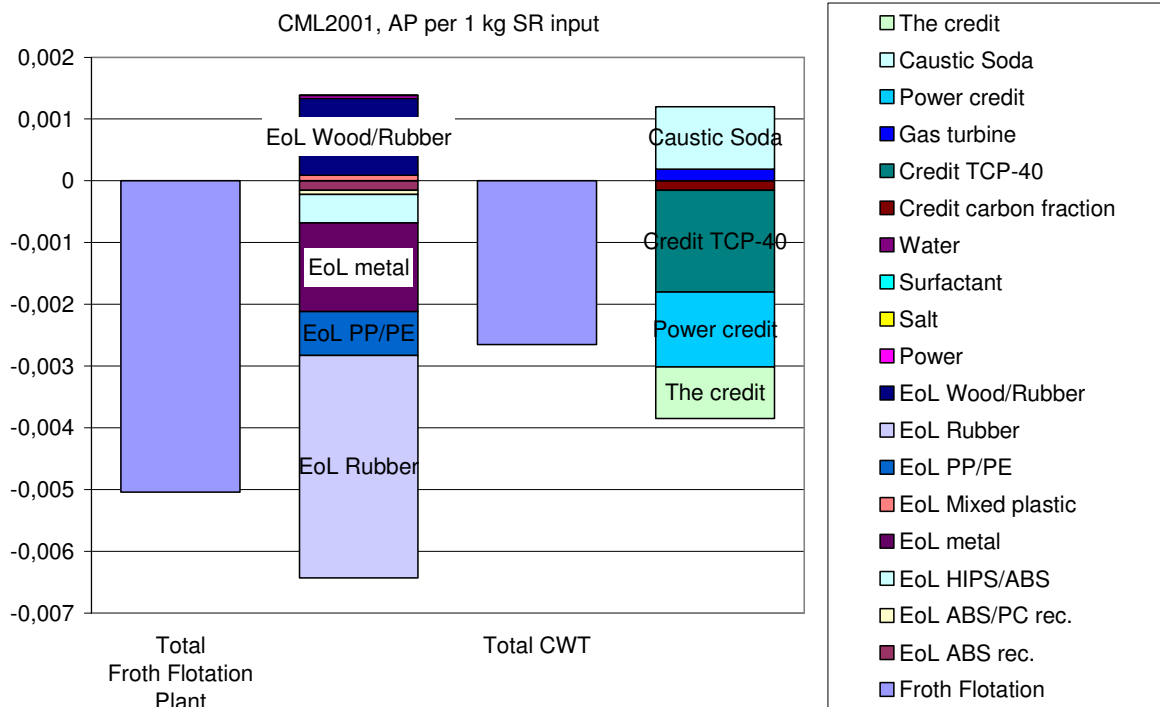


**Figure 7-6: MJ Primary energy demand per 1 kg of shredder residue**

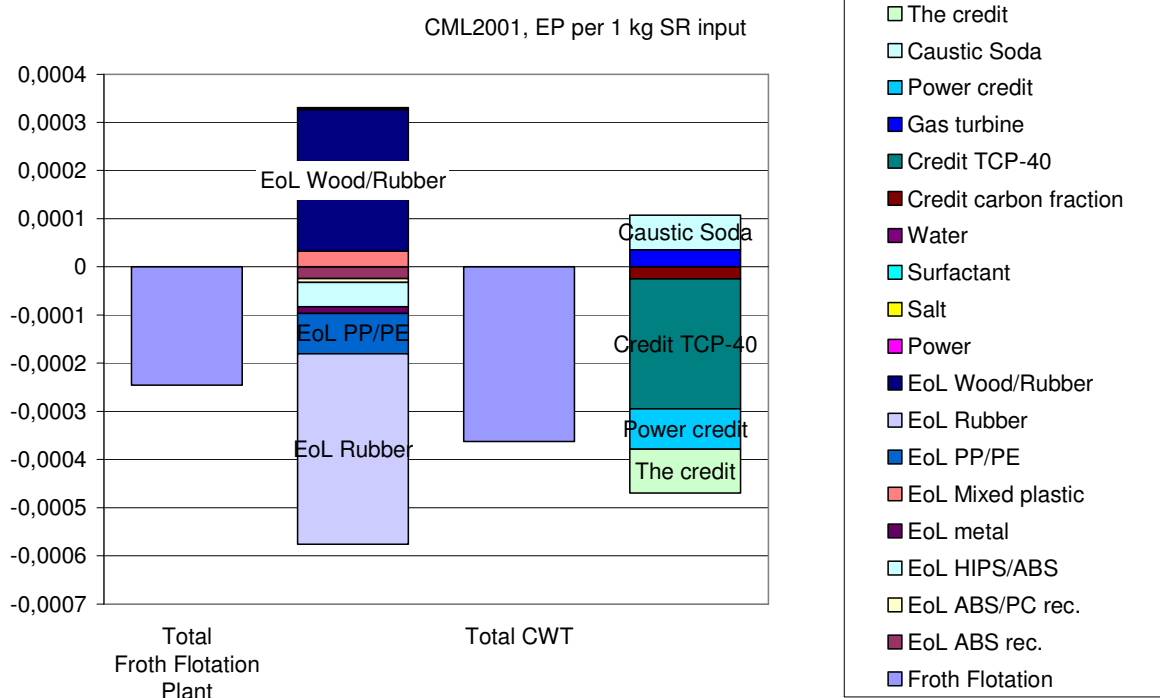
The quantitative numbers for the analyzed impact categories are displayed in Table 7-5 while the results are shown specific for each produced fraction and needed energy/ auxiliary material in Figure 7-7 to Figure 7-10.

**Table 7-5: Comparison of Argonne process – CWT process (Impact categories)**

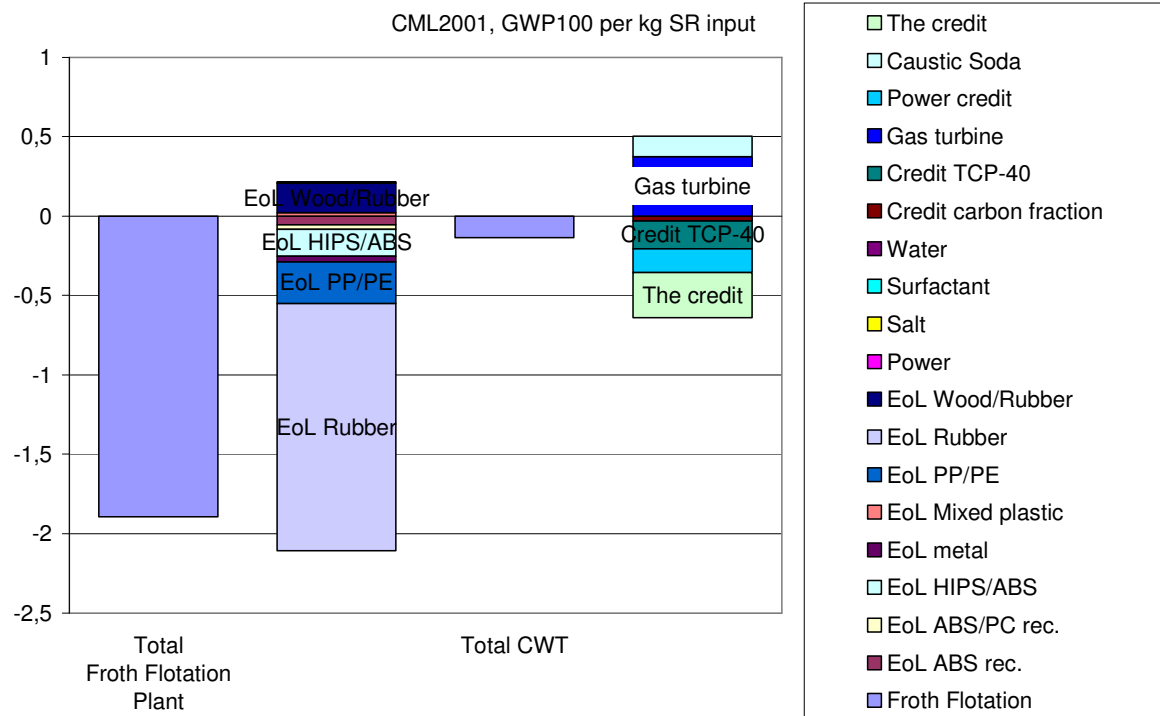
	ARGONNE process (Froth Flotation)	CWT process
AP [kg SO <sub>2</sub> -Equiv.]	-0.005	-0.003
EP [kg Phosphate-Equiv.]	-2.5E-4	-3.6E-4
GWP100 [kg CO <sub>2</sub> -Equiv.]	-1.89	-0.14
POCP [kg Ethene-Equiv.]	-0.004	-0.002



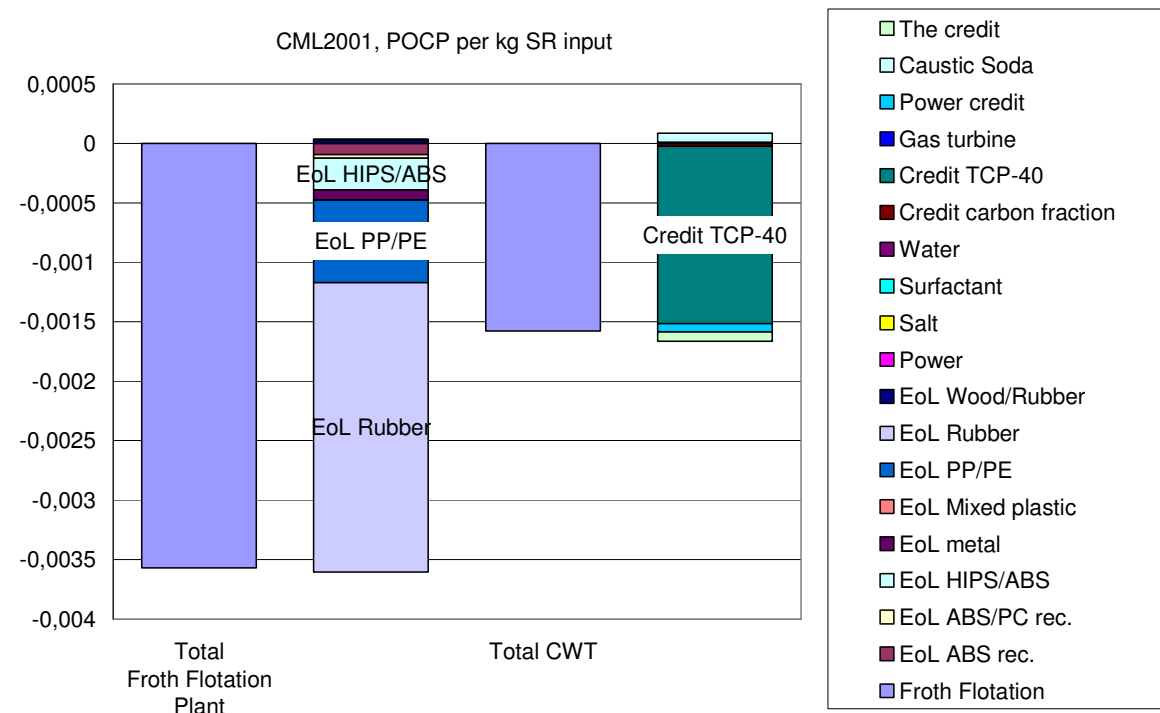
**Figure 7-7: kg SO<sub>2</sub>-Equiv. Acidification Potential (CML2001, AP) per 1 kg of shredder residue**



**Figure 7-8: kg Phosphate-Equiv. Eutrophication Potential (CML2001, EP) per 1 kg of shredder residue**



**Figure 7-9: kg CO<sub>2</sub>-Equiv. Global Warming Potential (CML2001, GWP100) per 1 kg of shredder residue**



**Figure 7-10: kg Ethene-Equiv. Photochem. Ozone Creation Potential (CML2001, POCP) per 1 kg of shredder residue**

The analysis of the impact categories showed that for all separated fraction by the ARGONNE process substituting materials and the produced fraction (TCP-40 oil and carbon) by the CWT process environmental benefits can be realized. The handling of the output



streams by energy recovery (ARGONNE) has a negative effect on the discussed impact categories while the handling of the produced gas by the gas turbine producing electricity and thermal energy for running the CWT process<sup>11</sup> results in a positive effect for the presented impact categories.

### 7.2.3 Summary comparison Argonne – CWT

The comparison of the two technologies showed, that both processes show benefits for primary energy demand, all considered impact categories and specific emissions. The environmental benefits are higher for the Argonne process compared to the CWT process except for the impact category EP and NO<sub>x</sub> emissions.

While the handlings of all produced fractions by CWT show overall benefits, this is not the case for all separated fraction of the Argonne process. The wood/ rubber and mixed plastics, which are given to energy recovery show burdens for most emissions and impact categories.

As the handling of organics by CWT result in overall environmental benefits, the possibility of combining both processes should be considered. If all organic fractions separated by Argonne which do not meet the requirements for substituting material for product application would be handled by CWT, the overall environmental benefit would be increased.

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<sup>11</sup> As more electricity and thermal energy is produced by the gas turbine, this amount is modelled substituting electricity from the US grid and thermal energy using natural gas.



## 8 Summary

The LCI model is one piece to meet VRP's internal goal of modeling the entire life cycle of a vehicle's end of life phase. It enables the user to analyze the environmental benefits of a complex process in a simple and time efficient way and supports the effort to identify what technology or composite of technologies provide the most beneficial way for handling shredder residue and the separated/ produced fractions from an environmental, energy and economic point of view.

The simulation of various shredder residue compositions using the LCI model showed that the methodology of Life Cycle Assessment can be used ideally to analyze the environmental impacts of the process as well as the ecological burden/ credits related to the separated material fraction.

The created LCI model enables ARGONNE to run simulations within specific boundary conditions by adding new potential applications for the separated fractions and adjusting the parameters for the shredder residue composition.

The analysis of the considered scenario showed that the usage of the ARGONNE plant result in environmental benefits for primary energy demand, CO<sub>2</sub>, SO<sub>2</sub> and VOC emissions and for the impact categories AP, EP, GWP100 and POCP while for NO<sub>x</sub> emissions no benefit has been identified.

The comparison of the ARGONNE process with Salyp and CWT showed that

- the Argonne process causes higher overall environmental benefits compared to Salyp (except AP/ SO<sub>2</sub> emissions) and therefore is the preferable process out of an environmental point of view,
- material recycling/ substitution should be preferred over energy recovery,
- for all considered emissions and impact categories the Argonne and CWT process showed environmental benefits,
- the Argonne process showed higher benefits compared to the CWT process except for EP and NO<sub>x</sub> emissions,
- the handling of organic fractions by CWT showed potential for improving the environmental impacts,
- negative effects are either caused by the consumption of power or the energy recovery of organic fractions which do not meet the requirements to be used in other applications.

From an environmental stand point the preferred solution would be a combination of Argonne and CWT with CWT handling all organic material streams which either do not meet the requirements for substituting material or if no application is available. This combination would achieve the highest amount of environmental improvement.

## 9 Literature

GABi 2003	GaBi 4: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP, Universität Stuttgart und PE Europe GmbH, Leinfelden-Echterdingen, April 2003.“
ARGONNE 2006	Personal information
CWT 2004	Personal information
CWT 2004	Protocol Testing Results Under VRP-PO 720
TROY POLYMERS 2004	Processing and testing of output products from thermal conversion process of two different shredder residue samples by CWT (VRP PO 700)
ISO 14040 : 1997	ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework, 1997
ISO 14041 : 1998	ISO 14041 Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis
ISO 14042 : 2000	ISO 14042 Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment, 2000
ISO 14043 : 2000	ISO 14043 Environmental Management – Life Cycle Assessment – Life Cycle Interpretation, 2000
VRP, PE EUROPE 2004	Life Cycle Inventory (LCI) of the Salyp SR separation process under VRP PO #722
VRP, PE EUROPE 2005	Life Cycle Inventory (LCI) of the CWT Thermal Conversion Process under PO #722 Amend A



## Appendix A Treatment of material fractions

### Appendix A 1 Mechanical Separation Plant

**Table 9-1: Detailed information on the material fractions of the Mechanical Separation Plant**

Fraction	Input Shredder	Starting Shredder Residue	Oversized Heavies	Oversized Polyurethane Foam Rich	1/4" Fines	Ferrous Rich	Non-Ferrous	Vacuum Lights	Fines	Lights	Moisture	Dust	Polymer Concentr
Polypropylene		289	0	0	0	4	9	19	0	13	0	0	244
Polypropylene (Filled)	PP	289											
ABS	PP (filled)	33	0	0	0	0	0	0	0	2	0	0	31
Polyethylene	ABS	154	0	0	0	1	2	3	0	0	0	0	148
Polystyrene	PE	154											
Nylon	PS	245	0	0	0	2	4	15	0	6	0	0	218
Polyvinyl Chloride	PS	63	0	0	0	1	2	3	0	1	0	0	56
PPO	Nylon	63											
PC/ABS	PVC	73	0	0	0	1	2	4	0	1	0	0	65
Polycarbonate	PVC	73											
Trace Plastics	PVC	132	0	0	0	0	0	0	0	0	0	0	132
Unidentified Plastics	PVC	132											
Rubber and Rigid Polyurethane	PPO	16	0	0	0	0	0	1	0	0	0	0	15
	PPO	16											
	PC/ABS	7	0	0	0	0	0	0	0	0	0	0	7
	PC/ABS	7											
	PC	123	0	0	0	0	0	3	0	0	0	0	120
	PC	123											
	Trace plastic	38	0	0	0	0	0	1	0	0	0	0	37
	Trace plastic	38											
	UI plastic	51	0	0	0	0	0	3	0	0	0	0	48
	UI plastic	51											
	Rubber	1324	6	0	0	2	49	14	0	3	0	0	1250
	Rigid PU	993	5			2	37	11					938
	Rigid PU	331	2			1	12	4					313
	Wood	52	0	0	0	0	0	0	0	0	0	0	52
	Wood	52											
	Metals	723	279	0	0	148	239	0	0	0	0	0	57
	ferrous	302	140			148							14
	nonferrous	421	140				239						43
	aluminium	351	140				198						13
	copper	61					31						30
	brass	10					10						
	Non-Plastics, Foams, and Fibers	5347	252	189	3217	5	60	335	750	65	0	443	31
	rocks	272	252		1	5	6		0		0	8	
	ferrous	1019			743				173				102
	moisture	525			383				89				53
	organics	2179			1589				371				219
	Flexible PU	408			298				69				41
	PET	1225			894				208				123
	Thermoset plastics	272			199				46				27
	PP	26			19				5				3
	PP filled	3			2				1				0
	ABS	16			12				3				2
	PE	24			17				4				2
	PS	6			4				1				1
	Nylon	7			5				1				1
	PVC	14			10				2				1
	PPO	2			1				0				0
	PC/ABS alloy	1			1				0				0
	PC	13			9				2				1
	Trace plastics	4			3				1				0
	Unidentified plastics	5			4				1				1
	Rubber	102			74				17				10
	Rigid PU	34			25				6				3
	Wood	6			4				1				1
	Ferrous metals	2			1				0				0
	Aluminium	1			1				0				0
	Copper	3			2				1				0
	aluminium	75			55				13				8
	ca	176			129				30				18
	cu	22			16				4				2
	mg	44			32				8				4
	mn	13			10				2				1
	si	313			228				53				31
	na	35			26				6				4
	ti	9			6				2				1
	Flexible PU	374		170	0		24	144	0	30		0	6
	PET fibers	294		19	1		30	191	0	35		0	17
	PP	0											0
	Wood	0											0
	Rubber	0											0
Moisture		1330	0	0	0	0	0	0	0	0	1330	0	0
	moisture	1330											
Total		10000	537	189	3217	164	367	401	750	91	1330	443	2511



## Appendix A 2 Froth Flotation Plant

**Table 9-2: Detailed information on the material fractions of the Froth Flotation Plant**

Fraction	Handling/Substitution	Substituted material
PP/PE	Product	PP
containing of Polypropylene Polyethylene Rubber and Rigid Polyurethane Non-Plastics, Foams, Fibers	----	----
Wood/Rubber	Energy Recovery	Energy Recovery
containing of Polypropylene Polypropylene (filled) ABS Polyethylene Polystyrene Nylon Unidentified Plastics Rubber and Rigid Polyurethane Wood Non-Plastics, Foams, Fibers	----	----
HIPS/ABS	Product	low grade PS
containing of Polypropylene (filled) ABS Polyethylene Polystyrene Nylon PPO Trace Plastics Rubber and Rigid Polyurethane Wood	----	----
ABS	Product	ABS
containing of Polypropylene (filled) ABS Nylon PPO PC/ABS Trace Plastics Rubber and Rigid Polyurethane	----	----
Mixed Plastics	Energy Recovery	----
containing of ABS Nylon PPO Trace Plastics Unidentified Plastics Rubber and Rigid Polyurethane Wood	----	----
ABS/PC	Product	ABS/PC
containing of ABS PVC PC/ABS Polycarbonate Rubber and Rigid Polyurethane	----	----
Metal	Product	25% ferrous (steel) 75% nonferrous (70% copper/30% aluminium)
containing of Nylon PVC Polycarbonate Rubber and Rigid Polyurethane Metals	----	----
Rubber	Product	EPDM
containing of Polypropylene (filled) ABS Polystyrene Nylon PVC PC/ABS Polycarbonate Trace Plastics Unidentified Plastics Rubber and Rigid Polyurethane Wood Metals Non-Plastics, Foams, Fibers	----	----





## Appendix B Detailed information on the results of the Argonne plant

### Appendix B 1 Mechanical Separation Plant

Mechanical Separation	EoL FE fraction	EoL Lights	EoL NF fraction	EoL Oversized Heavies	EoL Oversized PU	EoL Vacuum Lights	Power
Burden	524	125	0	494	74	549	32724
Benefit	3814	4758	13938	10028	29854	20954	0
Total	-3290	-4633	-13938	-9534	-29780	-20404	32724

Figure 9-1: Detailed information on the burdens and benefits of the Mechanical Separation Plant (Primary energy demand in MJ)

Mechanical Separation	EoL FE fraction	EoL Lights	EoL NF fraction	Oversized Heavies	Oversized PU	Vacuum Lights	Power
Burdens	2,23E-08	1,52E+00	0,00E+00	2,10E-08	0,00E+00	6,69E+00	1,73E+01
Benefit	8,78E-01	7,72E-01	2,09E+01	2,82E+00	9,91E+00	3,40E+00	0,00E+00
AP	-8,78E-01	7,47E-01	-2,09E+01	-2,82E+00	-9,91E+00	3,29E+00	1,73E+01
Burdens	2,45E-03	2,83E-01	0,00E+00	2,31E-03	0,00E+00	1,25E+00	1,19E+00
Benefit	6,82E-02	1,44E-02	2,83E-01	2,03E-01	1,44E+00	6,36E-02	0,00E+00
EP	-6,58E-02	2,69E-01	-2,83E-01	-2,01E-01	-1,44E+00	1,18E+00	1,19E+00
Burdens	2,82E-01	1,80E+02	0,00E+00	2,66E-01	0,00E+00	7,94E+02	2,15E+03
Benefit	2,04E+02	1,08E+01	7,86E+02	6,05E+02	1,40E+03	4,75E+01	0,00E+00
GWP100	-2,04E+02	1,70E+02	-7,86E+02	-6,05E+02	-1,40E+03	7,47E+02	2,15E+03
Burdens	2,30E-04	6,08E-02	0,00E+00	2,17E-04	0,00E+00	2,68E-01	1,01E+00
Benefit	1,33E-01	7,23E-02	1,33E+00	3,88E-01	6,59E-01	3,18E-01	0,00E+00
POCP	-1,33E-01	-1,15E-02	-1,33E+00	-3,87E-01	-6,59E-01	-5,07E-02	1,01E+00

Figure 9-2: Detailed information on the burdens and benefits of the Mechanical Separation Plant (Selected impact categories)

Mechanical Separation	EoL FE fraction	EoL Lights	EoL NF fraction	EoL Oversized Heavies	EoL Oversized PU	EoL Vacuum Lights	Power
Burden	0	178	0	0	0	783	2058
Benefit	176	0	731	546	1255	0	0
Total	-176	178	-731	-546	-1255	783	2058

Figure 9-3: Detailed information on the burdens and benefits of the Mechanical Separation Plant (CO<sub>2</sub> emissions)



## Appendix B 2 Froth Flotation Plant

Froth Flotation	EOI ABS	EOI ABS/PC	EOI HIPS/ABS	EOI Metal	EOI Mixed plastic	EOI PP/PE	EOI Rubber	EOI Wood/Rubber	Power	Salt	Surfactant	Water
Burdens	0	0	0	51	70	0	0	568	405	46	31	18
Benefit	7212	2981	26093	3208	2666	48650	211217	10841	0	0	0	0
Total	-7212	-2981	-26093	-3157	-2596	-48650	-211217	-10273	405	46	31	18

Figure 9-4: Detailed information on the burdens and benefits of the Froth Flotation Plant (Primary energy demand in MJ)

Froth Flotation	EOI ABS	EOI ABS/PC	EOI HIPS/ABS	EOI Metal	EOI Mixed plastic	EOI PP/PE	EOI Rubber	EOI Wood/Rubber	Power	Salt	Surfactant	Water
Burdens	0,00E+00	0,00E+00	0,00E+00	2,17E-09	8,51E-01	0,00E+00	0,00E+00	7,35E+00	2,14E-01	3,16E-02	2,76E-03	3,15E-03
Benefit	7,04E-01	2,96E-01	2,13E+00	6,53E+00	4,33E-01	3,22E+00	1,64E+01	1,70E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
AP	-7,04E-01	-2,96E-01	-2,13E+00	-6,53E+00	4,19E-01	-3,22E+00	-1,64E+01	5,65E+00	2,14E-01	3,16E-02	2,76E-03	3,15E-03
Burdens	0,00E+00	0,00E+00	0,00E+00	2,38E-04	1,59E-01	0,00E+00	0,00E+00	1,37E+00	1,48E-02	5,12E-03	2,72E-04	2,80E-04
Benefit	1,10E-01	3,87E-02	2,29E-01	6,31E-02	8,09E-03	3,81E-01	1,80E+00	3,13E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00
EP	-1,10E-01	-3,87E-02	-2,29E-01	-6,29E-02	1,51E-01	-3,81E-01	-1,80E+00	1,34E+00	1,48E-02	5,12E-03	2,72E-04	2,80E-04
Burdens	0,00E+00	0,00E+00	0,00E+00	2,74E-02	1,01E+02	0,00E+00	0,00E+00	8,73E+02	2,66E+01	3,21E+00	1,11E+00	1,03E+00
Benefit	2,57E+02	1,28E+02	7,66E+02	1,68E+02	6,04E+00	1,19E+03	7,09E+03	2,38E+01	0,00E+00	0,00E+00	0,00E+00	0,00E+00
GWP	-2,57E+02	-1,28E+02	-7,66E+02	-1,67E+02	9,50E+01	-1,19E+03	-7,09E+03	8,49E+02	2,66E+01	3,21E+00	1,11E+00	1,03E+00
Burdens	0,00E+00	0,00E+00	0,00E+00	2,24E-05	3,41E-02	0,00E+00	0,00E+00	2,94E-01	1,25E-02	5,01E-03	1,25E-03	4,10E-04
Benefit	4,35E-01	1,37E-01	1,21E+00	3,89E-01	4,05E-02	3,16E+00	1,11E+01	1,54E-01	0,00E+00	0,00E+00	0,00E+00	0,00E+00
POCP	-4,35E-01	-1,37E-01	-1,21E+00	-3,89E-01	-6,45E-03	-3,16E+00	-1,11E+01	1,40E-01	1,25E-02	5,01E-03	1,25E-03	4,10E-04

Figure 9-5: Detailed information on the burdens and benefits of the Froth Flotation Plant (Selected impact categories)



<b>Froth Flotation</b>	<b>EoL ABS</b>	<b>EoL ABS/PC</b>	<b>EoL HIPS/ABS</b>	<b>EoL Metal</b>	<b>EoL Mixed plastic</b>	<b>EoL PP/PE</b>	<b>EoL Rubber</b>	<b>EoL Wood/Rubber</b>	<b>Power</b>	<b>Salt</b>	<b>Surfactant</b>	<b>Water</b>
Burden	0	0	0	0	100	0	0	853	25	3	1	1
Benefit	239	119	712	155	0	1104	6593	0	0	0	0	0
Total	-239	-119	-712	-155	100	-1104	-6593	853	25	3	1	1

**Figure 9-6: Detailed information on the burdens and benefits of the Froth Flotation Plant (CO<sub>2</sub> emissions)**

## Appendix C Appendix C Life Cycle Assessment – general description

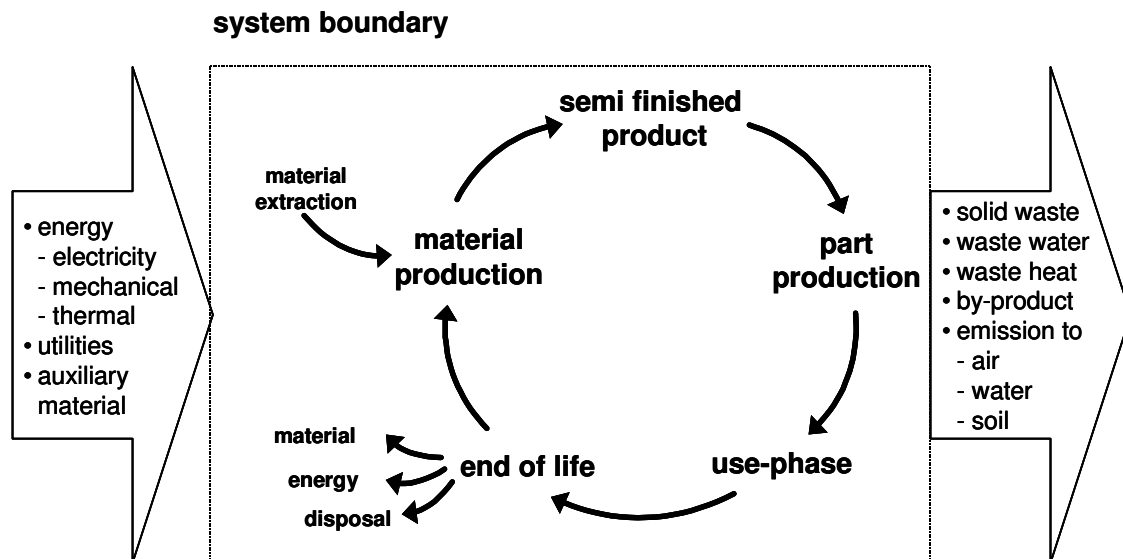
Life Cycle Assessment (LCA) is a suitable tool for analyzing and assessing the environmental impacts that are caused through production, use, and disposal of products or product systems for specific applications. LCA does not as a rule produce clear-cut straightforward assertions but gives diverse and complex results. It supports the process of decision-making by making complex issues transparent. The standard ISO 14040 defines LCA as follows:

LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

The concept of LCA is mainly concerned with the following basic aspects:

- the observation of the whole life cycle of a product - from raw material acquisition, processing, and production to its use, recycling and disposal.
- the coverage of all those impacts associated with the life cycle on the environment, such as raw material and energy consumption, use of land (input flows), emissions to air, water and land, as well as waste (output flows).
- aggregation and assessment of these impacts in view of the possible effects on the environment with the aim of assisting environment-oriented decisions.

The life cycle is represented in Figure 9-7. Transportation and external recycling or waste disposal need also to be taken into consideration.

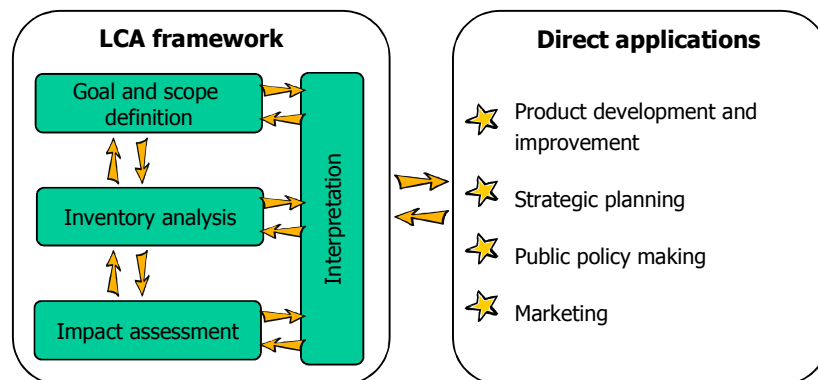


**Figure 9-7: Life cycle of product system (without transportation)**

According to the ISO 14040, the application of an LCA can assist in:

- identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- decision-making in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign);
- selecting the relevant indicators of environmental performance, including measurement techniques, and in

- marketing (e.g. an environmental claim, ecolabelling scheme, or environmental product declaration).



**Figure 9-8: Phases of an LCA**

An LCA is organized in the phases - goal and scope definition, inventory analysis, impact assessment and interpretation - as shown in Figure 9-8. The figure identifies the reciprocal influences of the individual phases and therefore shows the iterative character of an LCA. The application and the framework of the LCA have been purposely separated to show that an application or a decision is not automatically given through the results of an LCA study. The responsibility for an appropriate application of LCA data remains with the user; it cannot be taken on by the client or the practitioner of an LCA study. The single phases of an LCA have been described in the following chapters.

It must be emphasized that whilst the following points are to facilitate the understanding of an LCA, knowing the original content of the standard ISO 14040 is necessary in carrying out an LCA study, which conforms to the ISO. LCAs cannot cover all interactions with the environment. In this case, other tools must be used to fully observe the environmental impacts.

### Goal and Scope

The goal definition is of central importance, since the results, as a rule, are related to the respective question. The following points must be documented in the goal definition:

- intended application,
- reasons for carrying out the study, and
- intended audience.

Following the requirements established in ISO 14040, the goals could be:

- the weak points analysis in the production/the optimization of production /EoL processes;
- the accompanying assessment in the development of new components / design options;
- the optimization of total system by analyzing the system performance of the automobile;
- decision-making assistance in marketing;
- the optimization of the production of a component;



- the get an understanding of the environmental impact / benefits of different life cycle stages of an automobile.

Most of these goals are to be seen in terms of the whole life cycle. Further goals of such a study could be:

- the assistance of strategic decisions, and
- the recognition of possible influences of the social and political context and the identification of consequences resulting from political measures (e.g. in energy politics/Kyoto/emissions standards).

Defining the scope contains, in essence, the following points:

- system description,
- fundamental procedures, and
- data requirements.

### **System description**

The *system description* contains an analysis of the system with a description and a transparent presentation (e.g. flow charts). An important step in the system description is the definition of the functional unit<sup>12</sup>. The spatial and temporal system boundaries are then defined (space and time under observation).

### **Fundamental procedures**

Defining and documenting the fundamental procedures is important when conducting an LCA. That includes basic rules as well as specific issues. These could be, for example, the desired level of detail and depth or the choice of impact categories within the study. The application of cut-off criteria (for input and output flows) which allow the exclusion of insignificant contributions is to be described. If a system produces several products the input and output flows have to be allocated to each product. These allocation procedures must also be shown.

### **Data requirements**

The data quality has a significant influence on the LCA results. Depending on the goal, the requirements are to be formulated on the quality of data (e.g. on its precision, completeness and representativity). In this context, the sources of the data (of the LCA to be carried out) should be mentioned and the used database with reference to the pre-stages (e.g. energy provision and fabricated materials etc.) should be documented. Any assumptions that are taken should be mentioned.

### **Life cycle inventory analysis**

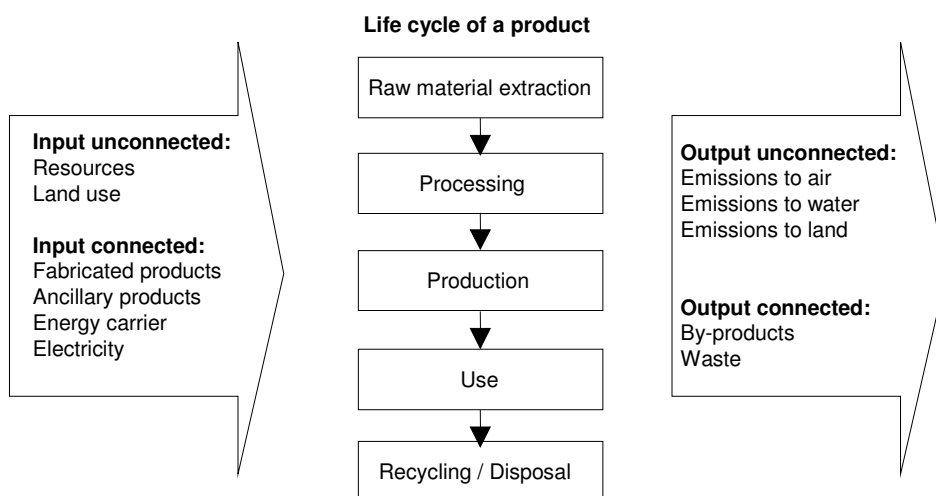
The main purpose of an inventory analysis in the context of data collection consists of the identification and quantification of the relevant input and output flows over the whole life cycle of a product. With these, one must also count, among others, the use of resources and the use of land, raw materials, fabricated products, auxiliary materials, energy carriers, and electricity (input). Emissions to air, water and land as well as waste and by-products (output) must also be recorded in an inventory analysis. In observing the whole

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<sup>12</sup> The functional unit specifies the function of the product system being studied and its efficiency. It serves as a reference for the established environmental impacts.

life cycle, it is ascertained that no environmental burdens have been shifted to other life phases and have therefore not been taken into account.

After the actual data collection, those input flows, which contain a primary chain, that is, those input flows under observation that cannot be directly taken from the crust of the earth (e.g. electricity), must be connected with the respective pre-stages. This means that all the necessary expenditure needed in providing the input flows (e.g. in the production processes or transportation) must also be taken into consideration on entering the system. Appropriate cut-off criteria are to be defined so as not to increase the work unnecessarily when re-pursuing the primary chains.



**Figure 9-9: Examples of input and output flows in the life cycle of a product.**

Data calculation is likewise a component of an inventory analysis. The question of allocation is here especially of importance. An allocation should always be carried out when dealing with systems involving multiple products (e.g. electricity and steam in a power plant). It is then important to define a key to allocate the environmental burdens of the production to the individual product. This also applies for by-products and recycling.

- Inventory analysis data are as a rule not suitable as a basis for comparative assertions. If comparative studies are being aimed at, this should be documented in the goal definition. In addition to this, a uniform process of working is needed for data collection and calculation, which should be clearly illustrated.

### Life cycle impact assessment

The impact assessment is carried out on the basis of an inventory analysis data. These data are categorized according to their potential impact on the environment in so-called impact categories. These categories describe the potential environmental impacts and not the actual effects, since the real effects depend on broader parameters, which are not registered by an LCA. This includes, for example, spatial and temporal parameters since an assertion over actual environmental impacts is connected with the where and when the emissions have actually been released.



Such an impact category is, for instance, the global warming potential. All emissions that produce a potential contribution to the greenhouse effect are assigned to this category. The most well known emission in this category, due to the current discussion, is carbon dioxide. In classifying the inventory data according to their potential environmental impacts, an aggregation of the number of impact categories takes place. The number of the data is therefore considerably reduced and the results can be better interpreted by referring directly to the environmental impacts. Since the inventory data are related to the functional unit, this relation also exists in the life cycle impact assessment. These results and data obtained from the inventory analysis can be used for the interpretation phase of an LCA.

### **Life cycle impact assessment according to ISO 14042**

The standard ISO 14042 divides the phases of the impact assessment into mandatory and optional elements. The mandatory elements are:

- choice of impact categories,
- classification, and
- characterization.

The optional elements are:

- normalization,
- grouping,
- weighting, and
- data quality analysis.

The first step within the framework of an impact analysis is *the choice of impact categories* in connection with the scope and goal definition. The choice of impact categories will be dealt with in detail later.

*Classification* comes next, where the inventory data is assigned to categories according to their impact. For instance, carbon dioxide emissions contribute to the greenhouse effect. If a substance contributes to several impact categories, it has to be taken into account, in all of these categories. Such a case is, for example, nitrogen oxide, which is the cause of nitrification and acidification in lakes and soil.

Classification is followed closely by *characterization*. Every substance is assigned a potential impact in the impact category under study. The potential impact of a substance is set in relation to a dominant factor in the category. The reference unit for the greenhouse potential is 1 kg carbon dioxide. The values, which result from it, are described as impact factors. After multiplying the emissions by the impact factors, they are added to the respective impact category and summed up to a total.

The classification and characterization results make up the profile of the product or product system under study. These profiles may be used as modules for the impact assessment of systems, in which these products are primary stages or primary products. However, a prerequisite for this is that all aspects of the impact assessment of the system, which have been carried out, follow the standardized rules.

The optional element called *normalization* sets the contribution of a product system and, for example, the contribution of a country or continent, in relation to each other. In this





way, the significance of the contribution of a product assigned to an impact category can be shown. So one can then understand to which impacts on the environment the system under study contributes relatively mostly. This, however, does not provide any assertions on whether one impact category is more important than the other from an ecological point of view.

Within *grouping*, each impact category may be defined in groups (e.g. subdividing impact categories into regional, local, and global groups) or in terms of a sequence of impact categories, which have been established, according to their (subjective) significance. This does not imply that the results of different impact categories may be transformed into one indicator, in other words, the grouping still does not imply an aggregation of data.

The *weighting*, on the other hand, aims at an aggregation of impact categories. The method to model impact categories is still being developed for some environmental impacts. Therefore a weighting of all environmental impacts is, at present, still in its theoretical phase. What needs to be taken into consideration is that a weighting of such different environmental impacts is based on values and therefore cannot be attributed to scientific knowledge. In special cases however, the impact assessment results can be further aggregated in an evaluation. A prerequisite for this is that the impact assessment results maintain their transparency and accuracy and that the data before weighting is available. A total aggregation to one single environmental indicator is not allowed in comparative studies according to ISO 14040.

As a last optional step, the standard deals with the *data quality analysis*. This step should support the validity of the analysis.

### **Choice of impact categories**

In the standard ISO/DIS 14042, no impact categories are defined for application. The requirements for the choice of impact categories are however set. These could be for example:

- conformance with the goal definition;
- comprehensive choice of environmental issues in relation to the product;
- clear citation of sources;
- explanation and description of the categories and working mechanisms;
- arguments for choice.

Over and above this, recommendations as to choice are given for example:

- international acceptance of the impact categories;
- avoidance of 'double counting' of the same impacts in several categories (e.g. by taking into consideration the impacts 'acidification' and 'proton input' in separate categories).

An interdisciplinary expert group (SETAC-Europe<sup>13</sup>) is currently developing recommendations for the best available models for impact categories. The choice of the impact categories should generally aim at sustainable development, preserving resources, the global protection of the eco-sphere, protecting human health and the stability of the ecosystems.

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<sup>13</sup> Society of Environmental Toxicology and Chemistry



Comparative LCAs could lead to different results depending on the choice of impact categories under study, which should be justified in the goal definition.

**Table 9-3: Impact categories that assess environmental impact**

Impact category/ aggregated inventory data	Short description	Examples
Depletion of resources	Non-sustainable raw material use	Petroleum or ore extraction
Greenhouse warming potential (GWP)	Emissions to air which influence the temperature of the atmosphere	CO <sub>2</sub> , CH <sub>4</sub> ....
Ozone depletion potential (ODP)	Emissions to air which deplete the tropospheric ozone layer	CFCs ....
Acidification potential (AP)	Emissions to air which cause acid rain	NO <sub>x</sub> , SO <sub>2</sub> , HCl, HF ....
Nitrification potential (NP)	Nitrification of lakes, rivers and soil	P and N compounds
Photochemical ozone creation potential (POCP)	Emissions to air which lead to ozone production at ground level	Hydrocarbons
Human toxicity potential (HTP)	Emissions to land, air and water which are harmful to health or genes	Heavy metals and dioxins
Ecotoxicity potentials (AETP and TETP)	Emissions to land, air and water, which disturb flora and fauna ecosystems	Heavy metals, acids, ....
Use of land and space	Duration and type of man-made change of land and space	Space for raw material extraction or production plants

In accordance with the above-mentioned aspects, the impact categories and their respective source are listed in Figure 9-9.

The methodology of impact assessment for some environmental impacts is still being developed. This applies especially for the toxicity potentials (HTP, AETP, and TETP) and the use of land and space.

Energetically used resources are separated into renewable and non-renewable. Fossil fuels like coal, petroleum, and natural gas belong to the non-renewable energy carriers. In the renewable energy, we find, for example, water and wind energy but also raw materials, which can be reproduced as long as they originate from sustainable cultivation. The expenditure specification in primary energy (PE) in mega joules (MJ), which is divided into renewable and non-renewable energy carriers, represents a common aggregation of energetically used resources. In addition, the use of secondary energy carriers has to be separately documented.

The treatment of waste (incineration and dump) in an LCA should be integrated into the system under study and its environmental effects assigned to the known impact categories. If this is not possible, the waste can be documented in the groups: overburden, ore processing residues, household waste, and hazardous waste.



### **Description of the impact categories**

In the following text, selected impact categories and their definition as well as the basic impact mechanisms and effects will be described in detail.

#### **Greenhouse effect**

The mechanisms of the greenhouse effect can be observed on a smaller scale in a car, in living rooms or as the name indicates in greenhouses. The incoming short-wave sunlight can penetrate the glassing almost unhampered and is transformed into long-wave infrared radiation when coming into contact with non-transparent elements or objects found in the room. The long-wave infrared radiation cannot leave the room unhampered. The occurring radiation energy is therefore greater than that energy, which is leaving the room. This leads to an increase in the room's temperature.

What has been described here can also be observed on a global scale. The occurring short-wave sun radiation comes into contact with the earth's surface and is partly absorbed (which directly leads to warming) and partly reflected as infrared radiation. The reflected part is absorbed in the troposphere<sup>14</sup> by so-called greenhouse gases<sup>15</sup> and is radiated again in every direction, so that it is partly radiated back to earth. This leads to a further warming.

Without this so-called natural greenhouse effect, the temperature would fall to about 18°C below zero. Life as we know it would be inconceivable, since the average temperature on earth is of about 15°C.

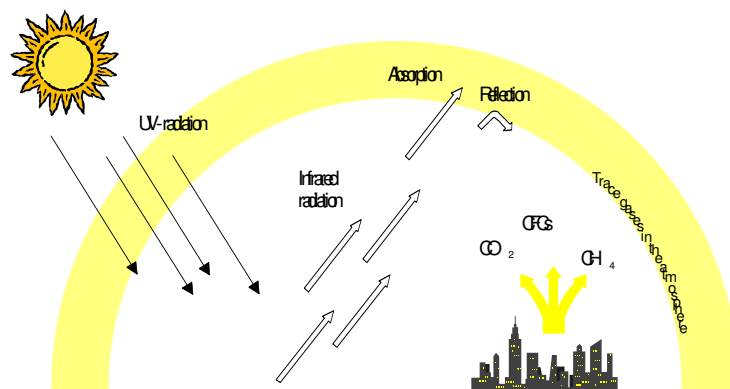
In addition to the natural greenhouse effect, there is also an anthropogenic aspect due to human activity, which contributes to the greenhouse effect. Greenhouse gases that are considered to be released anthropogenically are, for example, carbon dioxide, methane, and CFCs.

An increase in temperature on the earth's surface can lead to serious changes. One such example would be the increased melting of the polar icecaps, which is associated with a rise in sea level, whilst a change in the distribution of rainfall would lead to a shift in vegetation zones. The consequences have not been completely assessed. The fact is that there is an increase of about 1 °C/100 years on the earth's surface temperature. It is still of a controversy however, as to what extent this tendency has been caused by the anthropogenic greenhouse effect. The increase could have arisen from anthropogenic developments but it could also be due to natural fluctuations. The following illustration shows the most important mechanisms of an anthropogenic greenhouse effect.

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<sup>14</sup> Troposphere: Lower part of the atmosphere up to about a height of 10 km.

<sup>15</sup> Gases with a strong absorption band in the range of infrared (IR) light are called greenhouse gases [15]. Water steam and carbon dioxide are typical examples.



**Figure 9-10: Anthropogenic greenhouse effect**

The greenhouse potential is calculated in carbon dioxide equivalents ( $\text{CO}_2\text{-Eq.}$ ). That means that the greenhouse potential of an emission is given in relation to  $\text{CO}_2$ . Since the length of stay of a gas in the atmosphere must be included in the calculation, the time horizon under observation must always be given. This is usually given in relation to 100 years. In evaluating the greenhouse effect, it should be taken into consideration that the effects are global and of a long duration.

### Ozone depletion

Ozone is created when oxygen molecules are irradiated with short-wave UV-light. This leads to the building of the so-called ozone layer in the stratosphere (15 - 50 km of height). About 10% of this ozone reaches the troposphere through intermingling processes. In spite of its minimal concentration, the ozone layer is important for life on earth. Ozone absorbs the short-wave UV-radiation and releases it without any direction in longer wavelengths. Only a part of the UV-radiation reaches the earth.

Anthropogenic emissions cause the depletion of the ozone. This is generally known through reports on the hole in the ozone layer. Although these reports referred only to the Antarctica area, ozone depletion is now also discernible, if not to the same extent, on the mid-latitudes (e.g. Europe).

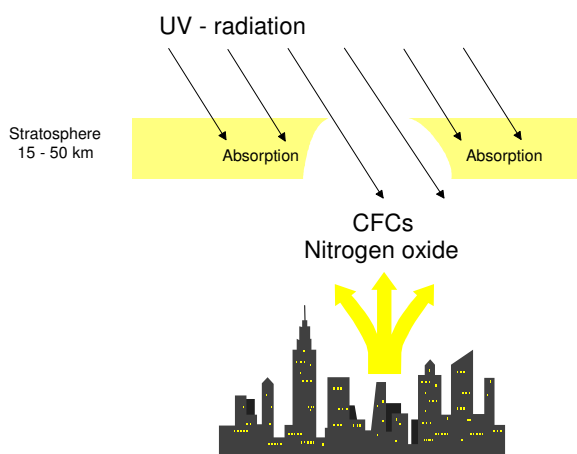
The substances that have a depleting effect on the ozone can be grouped essentially into two. These are the fluorine-chlorine-hydrocarbons (CFCs) and the nitrogen oxide ( $\text{NO}_x$ ). The following figure shows the essential aspects of ozone depletion.

One effect of ozone depletion is the warming up of the earth's surface. The sensitivity of man, animal and plant to UV-B and UV-A radiation is of special importance. Possible effects are, for example, growth changes or a decrease in harvest crops (Photosynthesis disruption), tumor indications (skin cancer and eye diseases) and the decrease of the sea plankton, which would affect the food chain.

In calculating the ozone depletion potential, the anthropogenic released halogenated hydrocarbons, which can destroy many ozone molecules, are first recorded. The so-called ozone damaging potentials (ODP: Ozone Depletion Potential) result from calculating different ozone relevant substances. This is done by calculating, first of all, a scenario of a fixed quantity of emissions of a CFC reference (CFC 11).

This results in an equilibrium state of a

total ozone reduction. The same scenario is considered for each substance under study whereby CFC 11 is replaced by the quantity of the substance. This leads to the ozone depletion potential for each respective substance, which is given in CFC 11 equivalents. An evaluation of the ozone depletion potential should take into consideration the long term, global and partly irreversible effects.



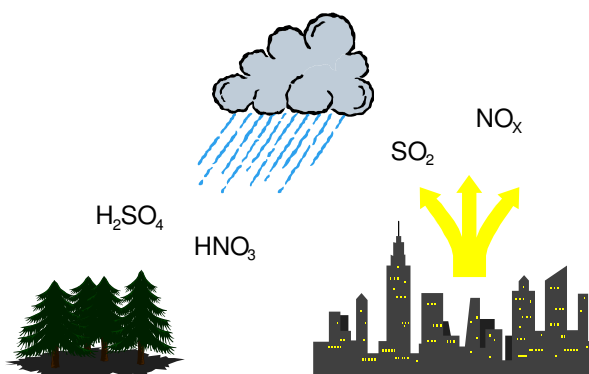
**Figure 9-11: Ozone depletion**

### Acidification

The acidification of soils and waters come about predominantly through the transformation of air pollutants into acids. This leads to a decrease of the pH-value of rainwater and fog from 5.6 to 4 and below that. Sulfur dioxide and nitrogen oxide and their respective acids ( $\text{H}_2\text{SO}_4$  and  $\text{HNO}_3$ ) produce relevant contributions. Damage occurs to ecosystems, of which the dying of forests is the most well known. This can lead to a direct or an indirect damage (nutrients being washed out of soils, an increased solubility of metals into the ground). But even buildings and building materials can get damaged. Examples of this are metals and natural stones, which are exposed to accelerated corrosion and dissolution. Figure 9-12 shows the most important aspects of acidification.

The acidification potential is given in sulfur dioxide equivalents ( $\text{SO}_2\text{-Eq.}$ ).

The acidification potential is described as the ability of certain substances to build and release  $\text{H}^+$  -ions [15]. Certain emissions can also be considered to have an acidification potential, if the given S-, N-, and halogen atoms are set in proportion to the molecular mass of the emission. The substance of reference is sulfur dioxide. In evaluating acidification, it should be taken into consideration that although it refers to a global problem, the effects, however, may differ regionally.



**Figure 9-12: Acidification**

### Nitrification

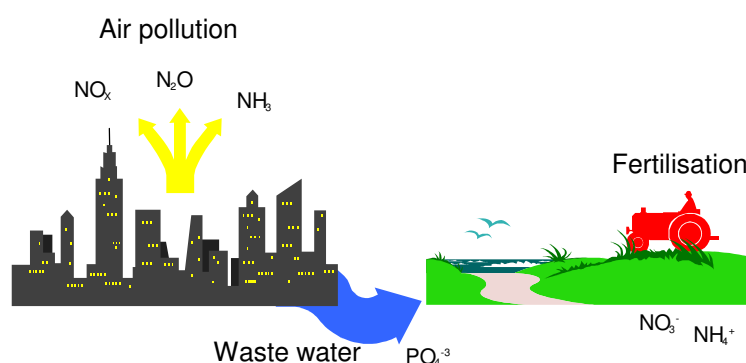
Nitrification is the enrichment of nutrients at a certain place. One differentiates between aquatic and terrestrial nitrification. Air pollutants, wastewater, and fertilization in agriculture contribute to nitrification. This results in an accelerated algae growth in waters, which in

turn, prevents sunlight from reaching the lower layers. This leads to a decreased photosynthesis associated with a lower oxygen production. Oxygen is also needed for the depletion of dead algae. Both effects cause a decreased oxygen concentration in the water that can finally lead to fish dying and to an anaerobic decomposition (without oxygen). Hydrogen sulfide and methane are produced. This can lead, among others, to the destruction of the eco-system.

Plants in a nitrified soil are more prone to diseases and pests and a weakening of their tissue system can be observed. If the nitrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate.

Nitrification causes increased nitrate content in ground water through washing out processes. Nitrate then reaches drinking water. Nitrate is in small amounts non-toxic. Most problematic is, however, the nitride as a reaction product of nitrate, which has toxic effects on people.

The nitrification potential is calculated in phosphate-equivalents ( $\text{PO}_4\text{-Eq}$ ). As in the acidification potential, one must also be aware of the fact that when it comes to the nitrification potential, the effects differ regionally.



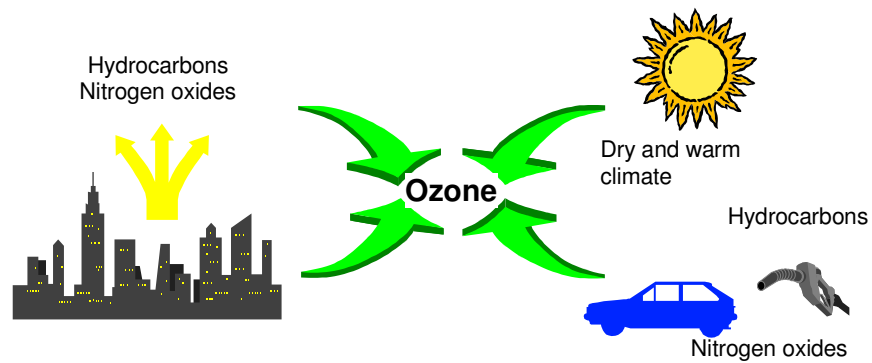
**Figure 9-13: Sources of nitrification**

### **Photochemical ozone creation potential (summer smog)**

Whilst the ozone has got a protection function in the stratosphere, it is classified as a damaging trace gas at ground level. Photochemical ozone formation in the troposphere, which is also referred to as summer smog, is suspected to cause damage to vegetation and material. High concentrations of ozone are toxic to humans.

Sun radiation and the presence of nitrogen oxides and hydrocarbons lead through complex chemical reactions to aggressive reaction products. Ozone is the most important reaction product. Nitrogen oxides alone do not cause high ozone concentration levels. Hydrocarbons must be present. Hydrocarbons emissions are released when dealing with petrol (storage, unloading and refueling etc.) or in connection with solvents or in the case of an incomplete combustion. Ozone concentration occurs in high temperatures, low air humidity, low air exchange, as well as high hydrocarbons concentrations. Since the presence of CO (usually from traffic) reduces the formed ozone to  $\text{CO}_2$  and  $\text{O}_2$ , the highest ozone concentration does not often occur in the immediate area of the source. It occurs rather in clean air areas (e.g. forests) and in areas where CO is hardly present. Photochemical ozone creation potential (POCP) is referred to as ethylene-equivalents ( $\text{C}_2\text{H}_4$ -

Eq.) in LCAs. In an evaluation, it must be taken into account that the actual ozone concentration levels depend on the type of weather. Similarly, ozone formation must be analyzed on a local scale.



**Figure 9-14: Ozone creation at ground level**

### Life cycle interpretation

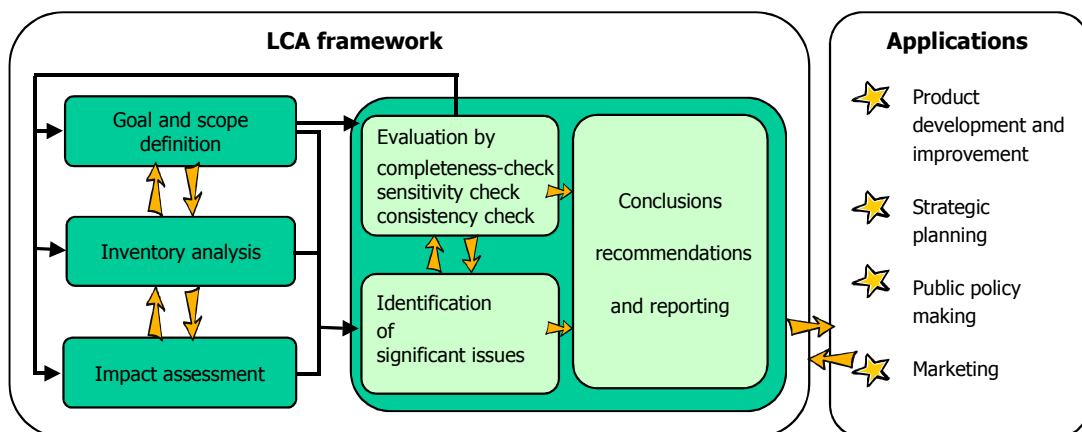
Within the framework of an evaluation, the results from the impact assessment and the inventory analysis are analyzed and conclusions and recommendations are established. A further aspect is the transparent presentation of the LCA results. The standard ISO 14043 comprises three interpretation elements:

- identification of the significant issues;
- evaluation which considers completeness, sensitivity and consistency checks;
- conclusions, recommendations, and reporting of the significant issues.

In order to determine the *significant issues* the main contributions of each impact category have to be identified (which emissions and/or which processes are dominant according to which category?). The relevant inventory data, which cannot be recorded through impact categories, must also be integrated into the study. Following the scope definition, the main contributions can be assigned to the individual process step, individual life phases, and the entire life cycle. Together with these results, the significant issues can now be established, since it is now also clear which processes or life phases are dominant.

To *evaluate the results* according to the standard a completeness check, a sensitivity check and a consistency check of the identified processes or life phases must be carried out. Completeness is checked by the mass and energy data analysis. Sensitivity is determined by calculating scenarios of different processes or different parameters. The effects of the different assumptions on the total result show the sensitivity. It must be ensured that all necessary information and data relevant to the interpretation are available and complete. It is also important to check to what extent uncertainties, for example, through the estimation of data due to data gaps, may influence the result. These uncertainties may be determined by the calculation of a minimal - maximal range, which reflect the possible extreme cases and the effects on the total results. The consistency check should ensure that the procedure is consistent with the goal and scope definition and that the methodology and rules have been accurately applied.

The third phase contains the conclusions, the recommendations, and the presentation of results. The relation between the interpretation phase and the other phases of LCA are illustrated in Figure 9-15.



**Figure 9-15: Relation between interpretation phase and other phases of LCA.**